Future Accelerator Challenges in Support of High-Energy Physics

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Introduction

- Historically, HEP has depended on advances in accelerator design to make scientific progress
  - cyclotron → synchrocyclotron → synchrotron → collider (circular, linear)
- Advances in accelerator design and performance require corresponding advances in accelerator technology
  - magnets, vacuum systems, RF systems, diagnostics, ...
- Accelerators enable the study of particle physics phenomena under (more or less) controlled conditions
- Cost of today's accelerator projects is high
  - international cooperation and collaboration are no longer optional
  - there is a danger of "pricing ourselves out of the market"

Accelerator Deliverables

- Particle accelerators are designed to deliver two parameters to the HEP user
  - energy and luminosity
- Energy is by far the easier parameter to deliver
  - and is easier to accommodate by the experimenters
    - higher luminosity invariably presents challenges to the detector
      - ...and to the accelerator physicist!
- Luminosity is a measure of collision rate per unit area
  - event rate for a given event probability ("cross section") is given by

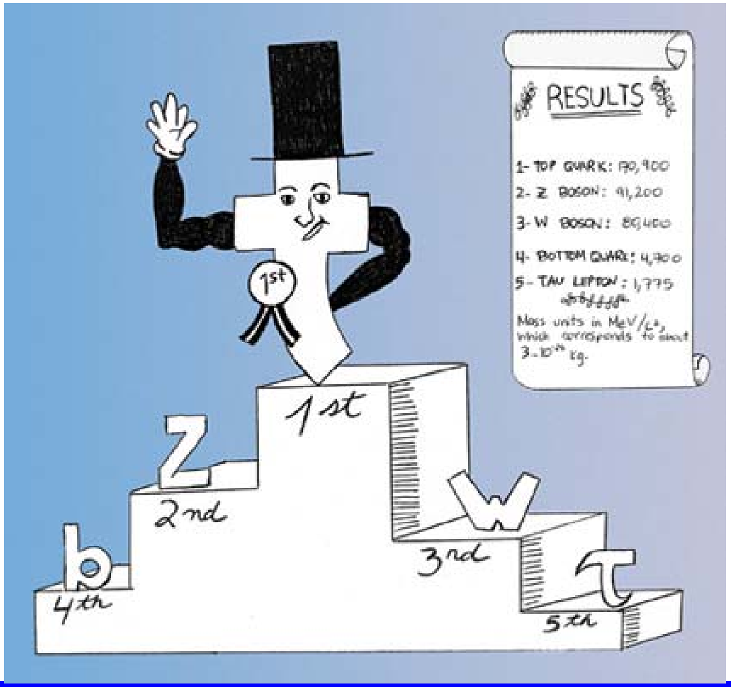
$$R = \mathcal{L} \sigma$$

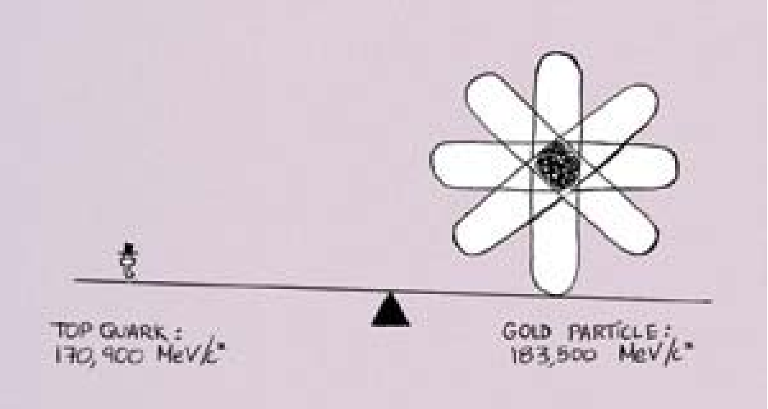
- For a collider with equal beam sizes at the IP, luminosity is given by $\dfrac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}$

$\Rightarrow$ Need intense beams and small beam sizes at IP

Particle Physics Questions (1)

- **There are two primary accelerator-related thrusts**
  - **understanding the origins of mass**
    - **what gives particles such different masses?**
      - **top quark has mass comparable to Au nucleus**
      - **neutrino mass is likely a fraction of an eV**





Particle Physics Questions (2)

- understanding why we live in a matter-dominated universe
  - why are we here?

- After Big Bang, equal amounts of matter and antimatter created
  - why didn't it all annihilate?
    - believed to be due to slight differences in reaction rates between particles and antiparticles
      - charge-conjugation–parity (CP) violation

- CP violation observed experimentally in "quark sector"
  - B factories were built to study this
    - unfortunately, CP violation in quark sector not large enough to explain observed baryon asymmetry
  - prevalent view is that required additional CP violation occurs in lepton sector
    - never observed; neutrinos are the hunting ground

Today's Machines

- High energy physics typically uses colliders (counter-propagating beams that collide at one or more interaction points "IPs")
  - until recently, colliders were single-ring machines that required beams of particles and antiparticles, e.g., e^- and e^+
    - to get higher intensities and more bunches, modern colliders use two rings and thus no longer require two beams that have opposite sign

$$\mathscr{L} = \frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}$$

- Colliders typically store one of two types of particles
  - hadrons (protons, heavier ions)
    - Tevatron $(\mathrm{p}-\bar{\mathrm{p}})$, RHIC (nuclear physics), LHC (p-p)
  - leptons (electrons)
    - CESR-c, PEP-II, KEKB

Today's Machine Limitations (1)

- Hadron colliders
  - protons are composite particles
    - only ≈10% of the beam energy is available for the hard collisions that make new particles
      - need $\mathcal{O}$(10 TeV) collider to probe the 1 TeV mass scale
    - desired high beam energy requires very strong magnets to store and focus beam in a reasonable-sized ring
  - antiprotons difficult to make
    - takes hours to replace them if beam is lost
  - using p-p collisions bypasses the second issue, but not the first
    - the demand for ever-higher luminosity has led the LHC to choose
      - p-p collisions
      - many bunches
      - two separate rings that intersect at select locations

Today's Machine Limitations (2)

- Lepton colliders (e^-e^+)
  - synchrotron radiation is the biggest challenge
  - emitted power in circular machine is

$$P_{SR}[\mathrm{kW}] = \frac{88.5\, E^4[\mathrm{GeV}]\, I[\mathrm{A}]}{\rho[\mathrm{m}]}$$

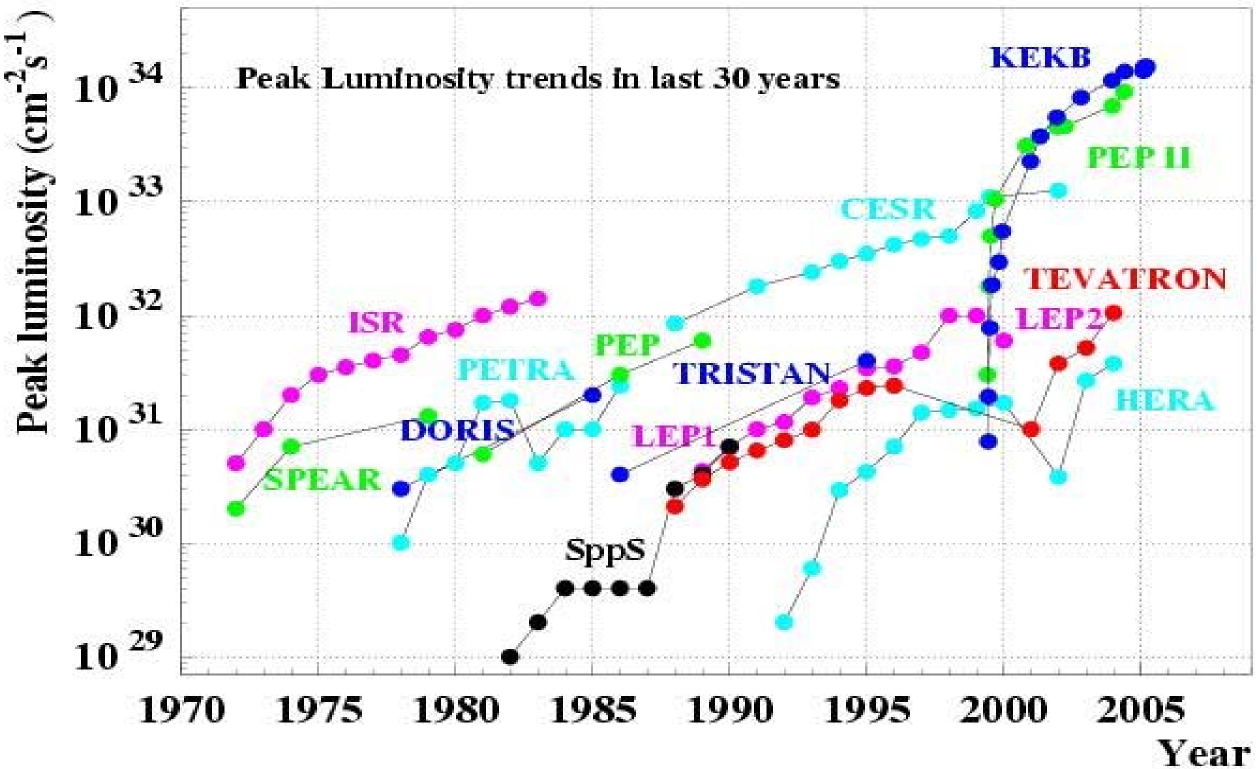
    - for a 1 TeV c.m. collider in the LHC tunnel (C = 27 km) with a 1 mA beam, radiated power would be 2 GW
      - would need to provide this power with RF
      - and remove it from the vacuum chamber!

- Approach for high energies is linear collider (ILC, CLIC)
  - footprint is large: 31 km in length (ILC); 48 km in length (CLIC)
    - too big to fit on-site at existing lab
  - single-pass acceleration is inefficient (no reuse of hardware)

Luminosity Performance

- e^+e^- colliders have made great strides in delivering luminosity in recent years
- Both KEKB and PEP-II quickly reached luminosities beyond 1×10^{34} cm^{-2} s^{-1}

New machines likely to be judged in comparison to these standards!



Future Machines

- At present, there are several machines on the drawing board to address the high-priority physics issues
  - not all of these are at the same stage of development
    - ILC and CLIC are furthest along in terms of R&D activities
  - most of these machines are very expensive
    - it is not likely that <u>all</u> of these will be built

- Precision frontier
  - ILC (e^+e^-)
  - Neutrino Factory (μ^+ or μ^-)
  - Super-B Factory (e^+e^-)

- Energy frontier
  - CLIC (e^+e^-)
  - Muon Collider ($\mu^+\mu^-$)

For reasons of personal taste and familiarity, I will tend to emphasize muon machines in this talk; these are the most novel, but not the most advanced, designs

Muon Accelerator Advantages

- Muon-beam accelerators can address both of the outstanding accelerator-related particle physics questions
  - neutrino sector
    - Neutrino Factory beam properties

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$

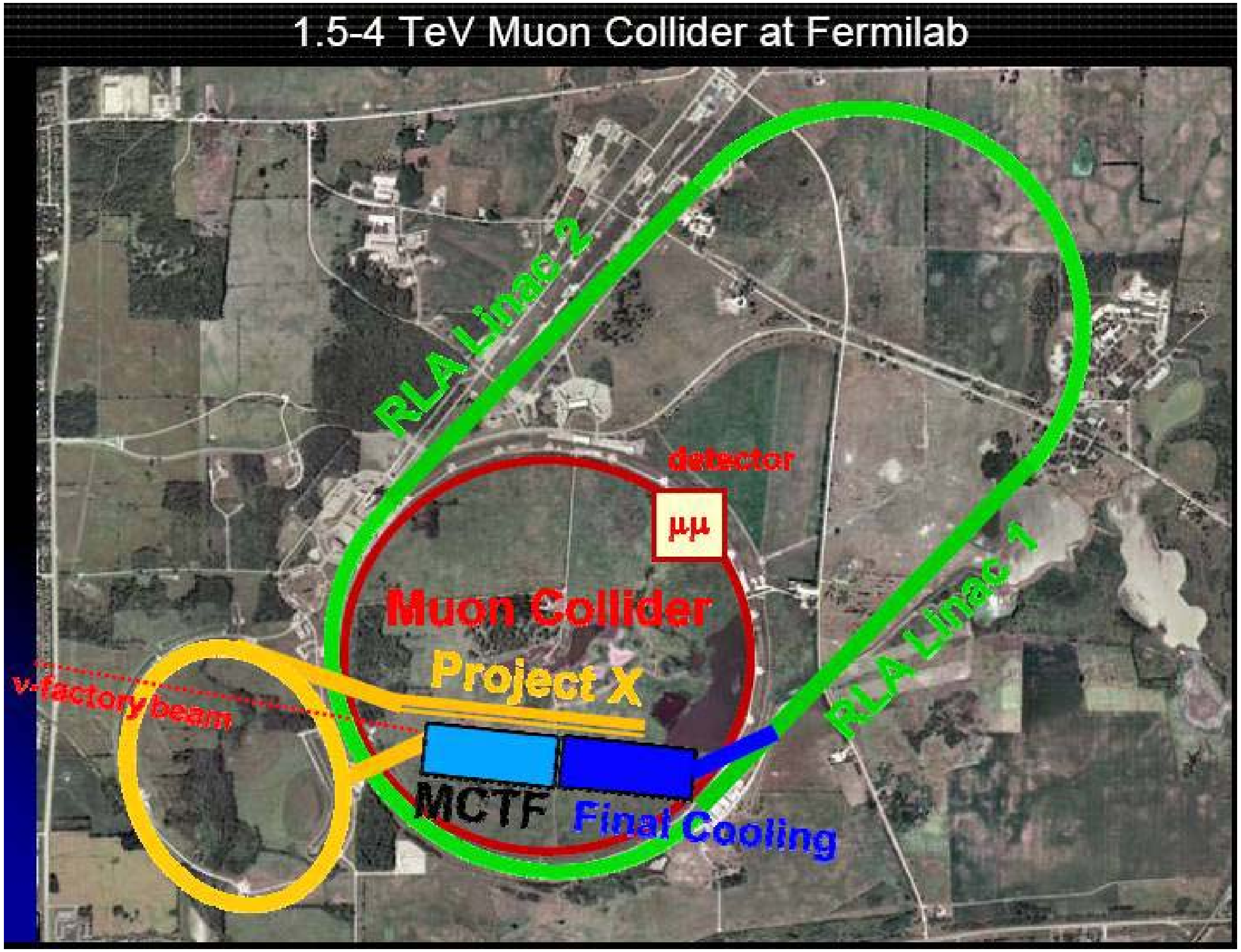
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \Rightarrow 50\% \bar{\nu}_e + 50\% \nu_\mu$$

Produces high energy neutrinos

    - decay kinematics well known
      - minimal hadronic uncertainties in the spectrum and flux
    - $\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable "wrong-sign" μ
  - energy frontier
    - point particle makes full beam energy available for particle production
      - couples strongly to Higgs sector
    - Muon Collider has almost no synchrotron radiation
      - narrow energy spread
      - fits on existing Lab sites

Muon Collider at Fermilab

- **Schematic of Muon Collider on Fermilab site**
  - it fits comfortably



Muon Beam Challenges

- Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
  - low production rate
    - need target that can tolerate multi-MW beam
  - large energy spread and transverse phase space
    - need solenoidal focusing for the low energy portions of the facility
      - solenoids focus in both planes simultaneously
    - need emittance cooling
    - high-acceptance acceleration system and decay ring

- Muons have short lifetime (2.2 μs at rest)
  - puts premium on rapid beam manipulations
    - presently untested ionization cooling technique
      - high-gradient RF cavities (in magnetic field)
    - fast acceleration system

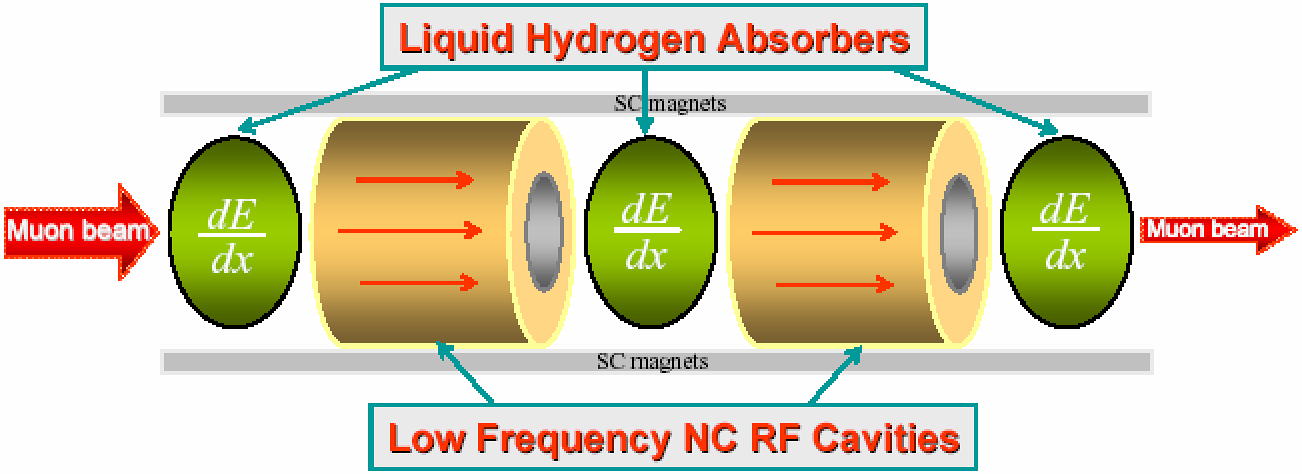
If intense muon beams were easy to produce, we'd already have them!

- Decay electrons give backgrounds in collider detector and instrumentation, and heat load to magnets (NF and MC)

Ionization Cooling (1)

- **Ionization cooling analogous to familiar SR damping process in electron storage rings**
  - **energy loss (SR or *dE/ds*) reduces p_x, p_y, p_z**
  - **energy gain (RF cavities) restores only p_z**
  - **repeating this reduces $p_{x,y}/p_z$ ($\Rightarrow$ 4D cooling)**

  - **presence of LH_2 near RF cavities is an engineering challenge**
    - **we get lots of "design help" from Lab safety committees!**



Ionization Cooling (2)

- **There is also a heating term**
  - for SR it is quantum excitation
  - for ionization cooling it is multiple scattering

- **Balance between heating and cooling gives equilibrium emittance**

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2}\left|\frac{dE_\mu}{ds}\right|\frac{\varepsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

Cooling Heating

$$\varepsilon_{x,N,equil.} = \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta m_\mu X_0 \left|\frac{dE_\mu}{ds}\right|}$$

  - prefer low $\beta_\perp$ (strong focusing), large X_0 and dE/ds (H_2 is best)

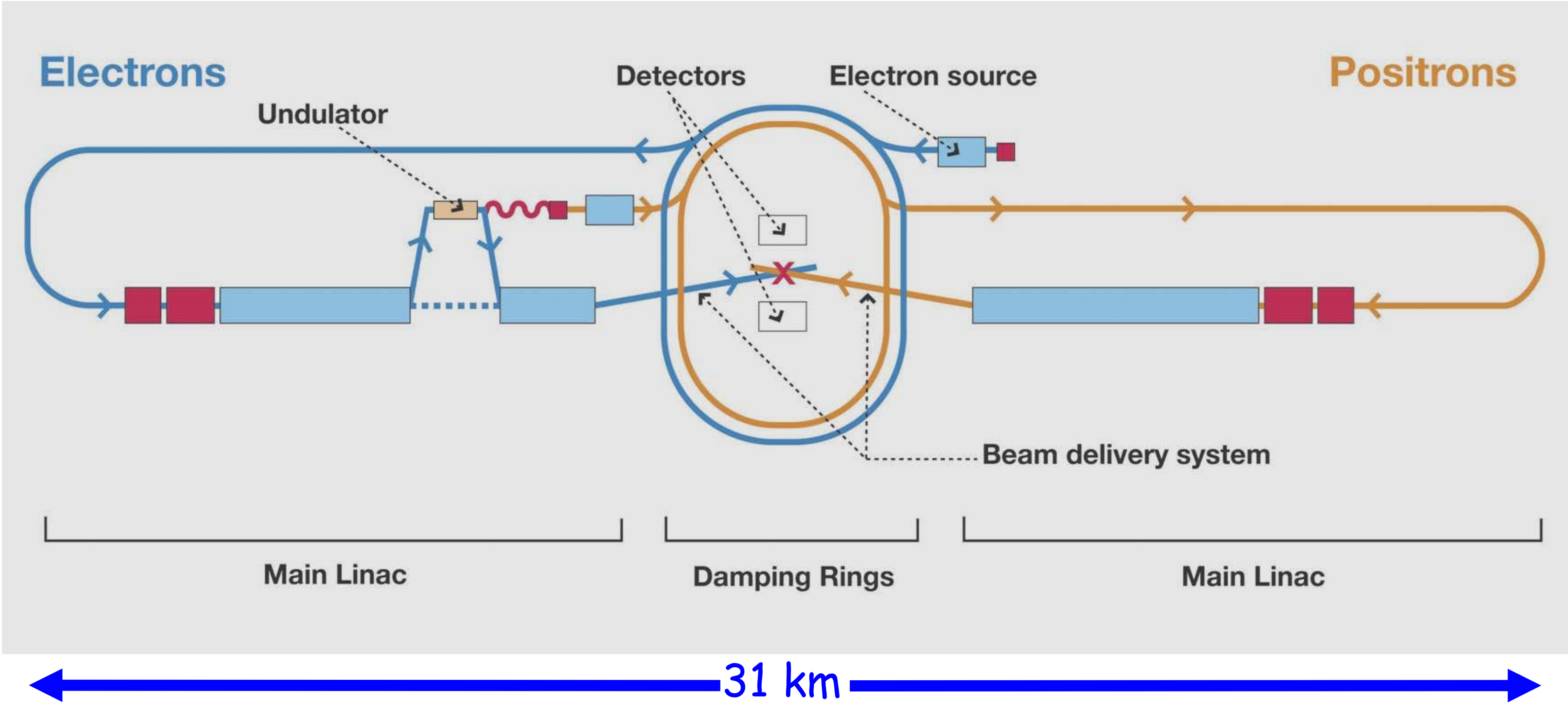
Ionization Cooling (3)

- **Merit factors for candidate MICE absorbers**
  - scaled as equilibrium emittance
    - requirements for Al windows and extended absorber for H_2 and He degrade these ideal values by about 30%
      - H_2 remains best, even with windows included

Material	$(dE/dx)_{min}$ (MeV g^{-1} cm^2)	X_0 (g cm^{-2})	Relative merit
Gaseous H_2	4.103	61.28	1.03
Liquid H_2	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18

ILC

- ILC is aimed initially at 0.5 TeV energy scale
  - two linacs + central damping ring complex
    - damping rings produce 2 pm-rad vertical emittance
  - technical challenges: low emittance, SRF gradient (31.5 MV/m)

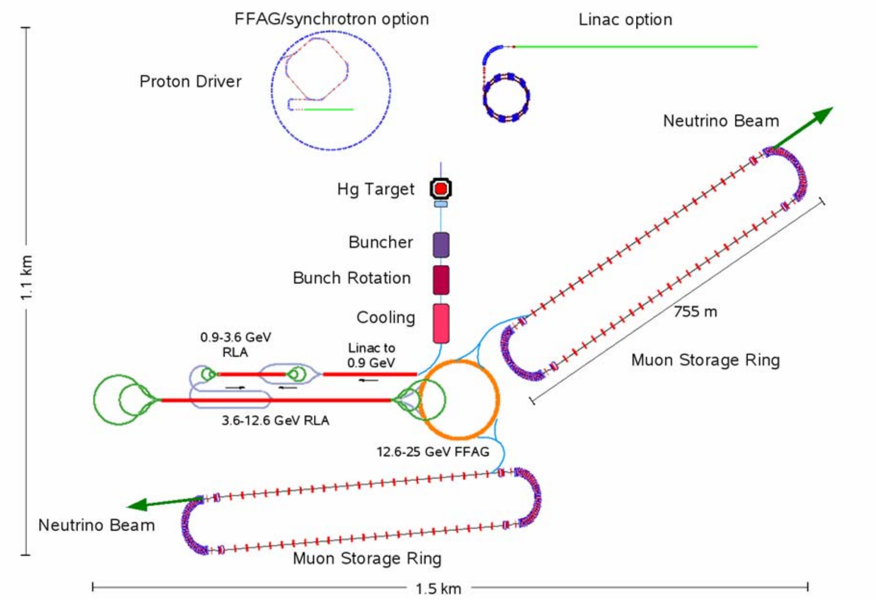


Neutrino Factory

- Neutrino Factory comprises these sections
  - Proton Driver
    - primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into $\mu \Rightarrow$ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse emittance $\Rightarrow$ MICE
  - Acceleration
    - 130 MeV $\rightarrow$ 20-50 GeV with RLAs or FFAGs
  - Decay Ring
    - store for 500 turns; long straight(s)

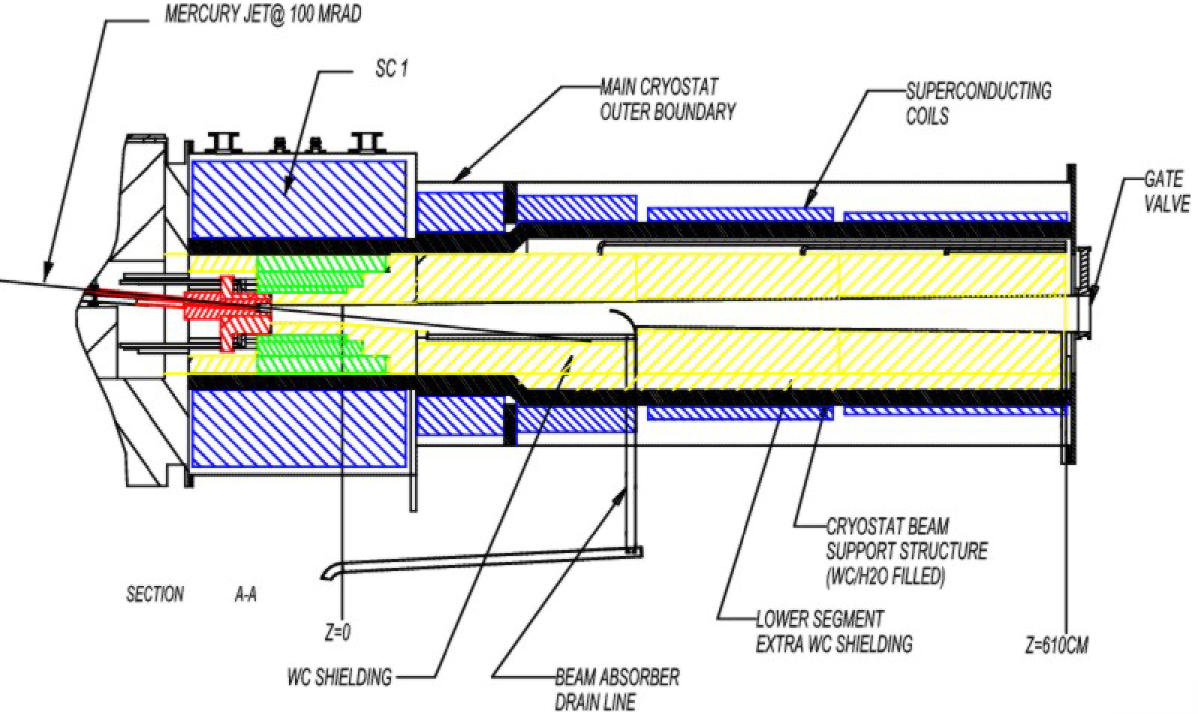
Aim for 10^{21} ν_e per year aimed toward detector(s)

ISS Baseline



Target

- **Favored target concept based on Hg jet in 20-T solenoid**
  - **jet velocity of 20 m/s establishes "new" target each beam pulse**

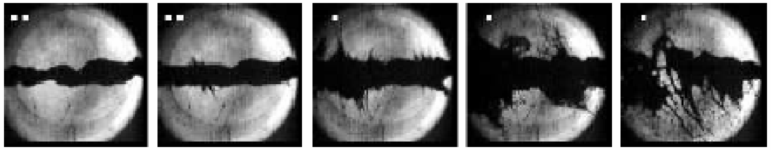


Target must survive bombardment by 4 MW proton beam

Target magnet is hybrid

SC outer coil, NC inner coil, and iron plug for field uniformity

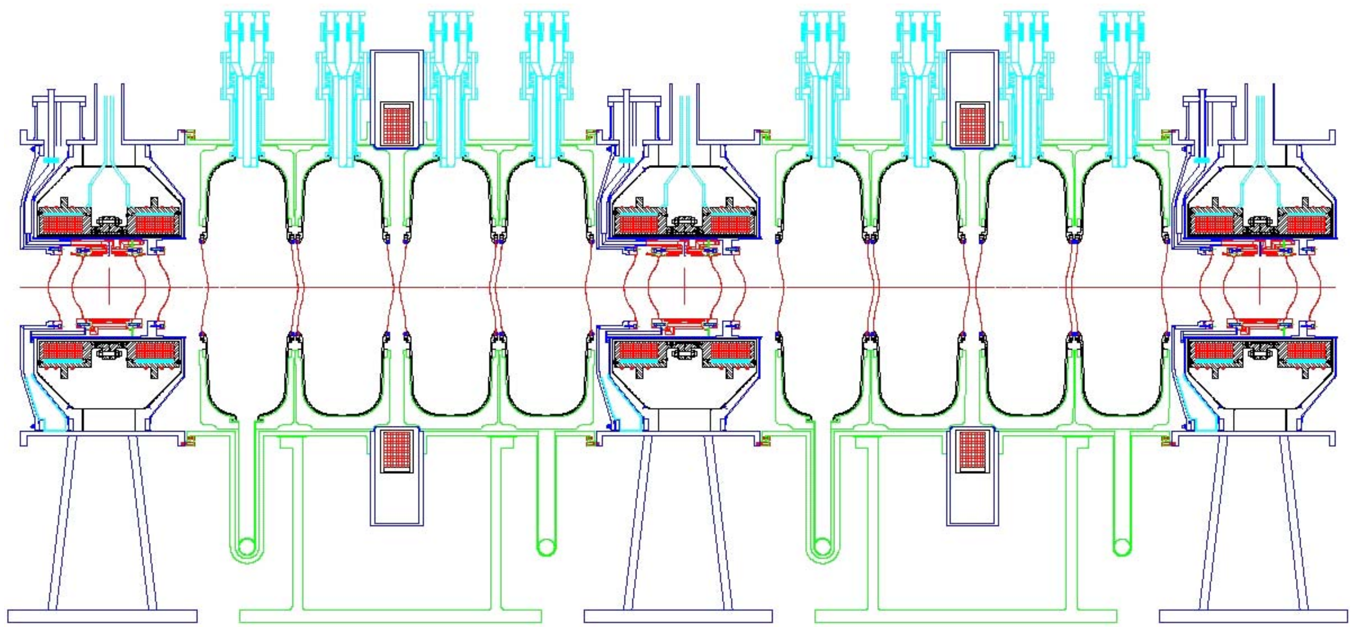
Hg jet



t = 0 0.75 2 7 18 ms

Cooling Channel Design

- **Study 2 channel is being tested in MICE**
  - challenges: RF in magnetic field; proximity of RF and LH_2 absorbers
- **Basic ingredients**
  - large solenoids, 201 MHz RF cavities, low-Z absorbers (LH_2 preferred)



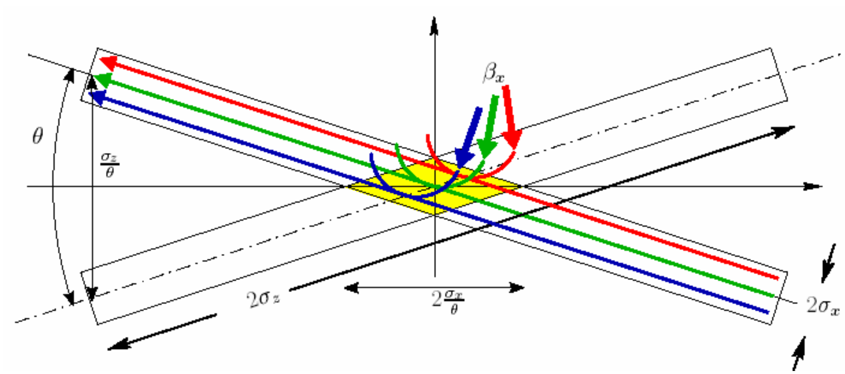
Study 2 channel ≡ MICE channel

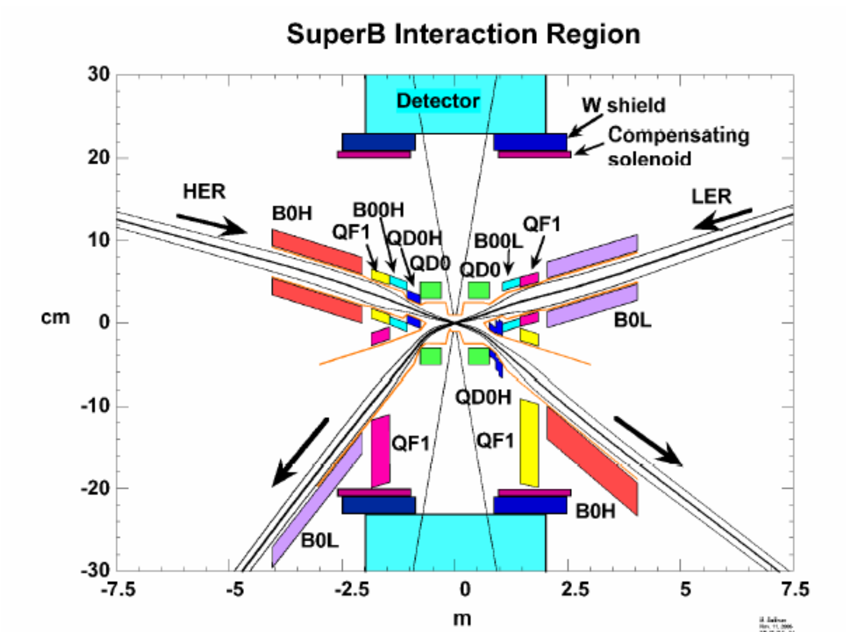
Super-B Factory

- Goal: run at $\Upsilon(4S)$ with luminosity of ~1×10^{36} cm^{-2} s^{-1}
- Use low-emittance rings with "crab waist" scheme to reduce effective beam size at IP
  - IR sextupoles suppress harmful synchrobetatron resonances

Frascati-SLAC design effort

Rings patterned after ILC DR design; would reuse many PEP-II components

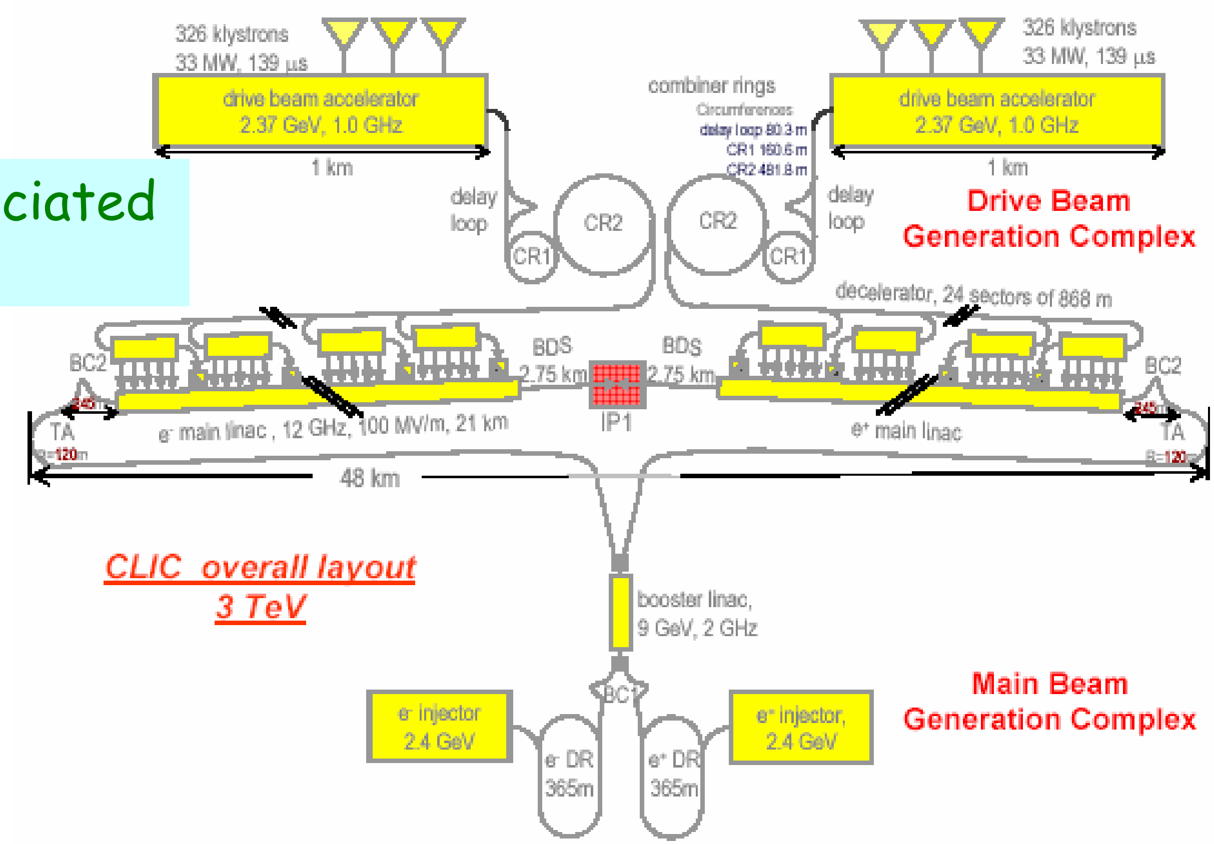




CLIC Layout

- CLIC is designed for a 3 TeV collision energy
  - has comparable *E* reach to LHC
    - uses "drive beam" for RF power generation

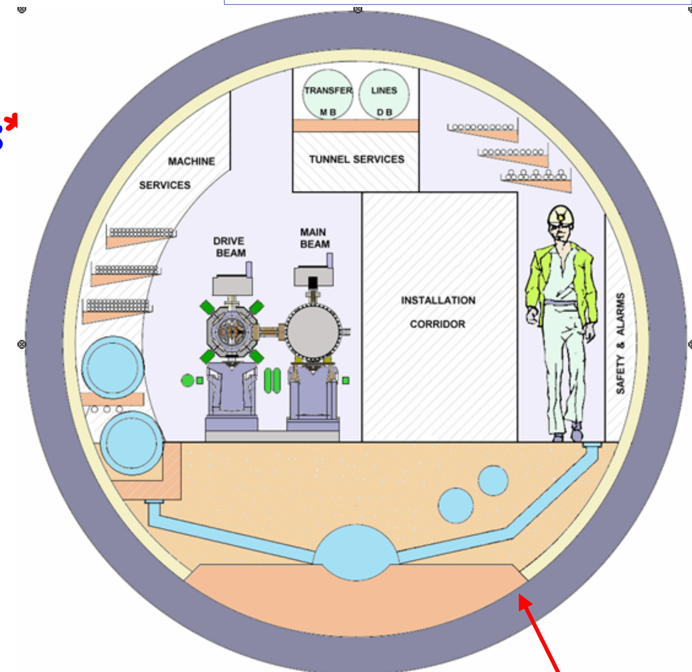
Main complications associated with drive beam



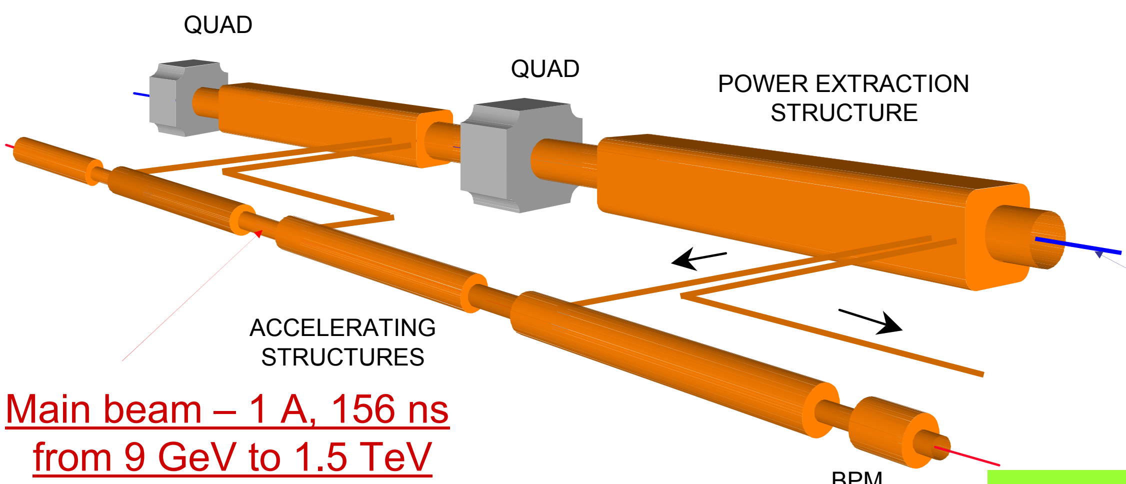
CLIC Features

- **Novel two-beam acceleration concept**
  - efficient, reliable, cost-effective
    - no active elements in main tunnel
  - modular; easily upgradeable to higher energies*
  - high gradients (>100 MV/m)
  - "compact" for 3 TeV linear machine (cf. ILC)

CLIC TUNNEL CROSS-SECTION



4.5 m diameter



Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV
100 MV/m

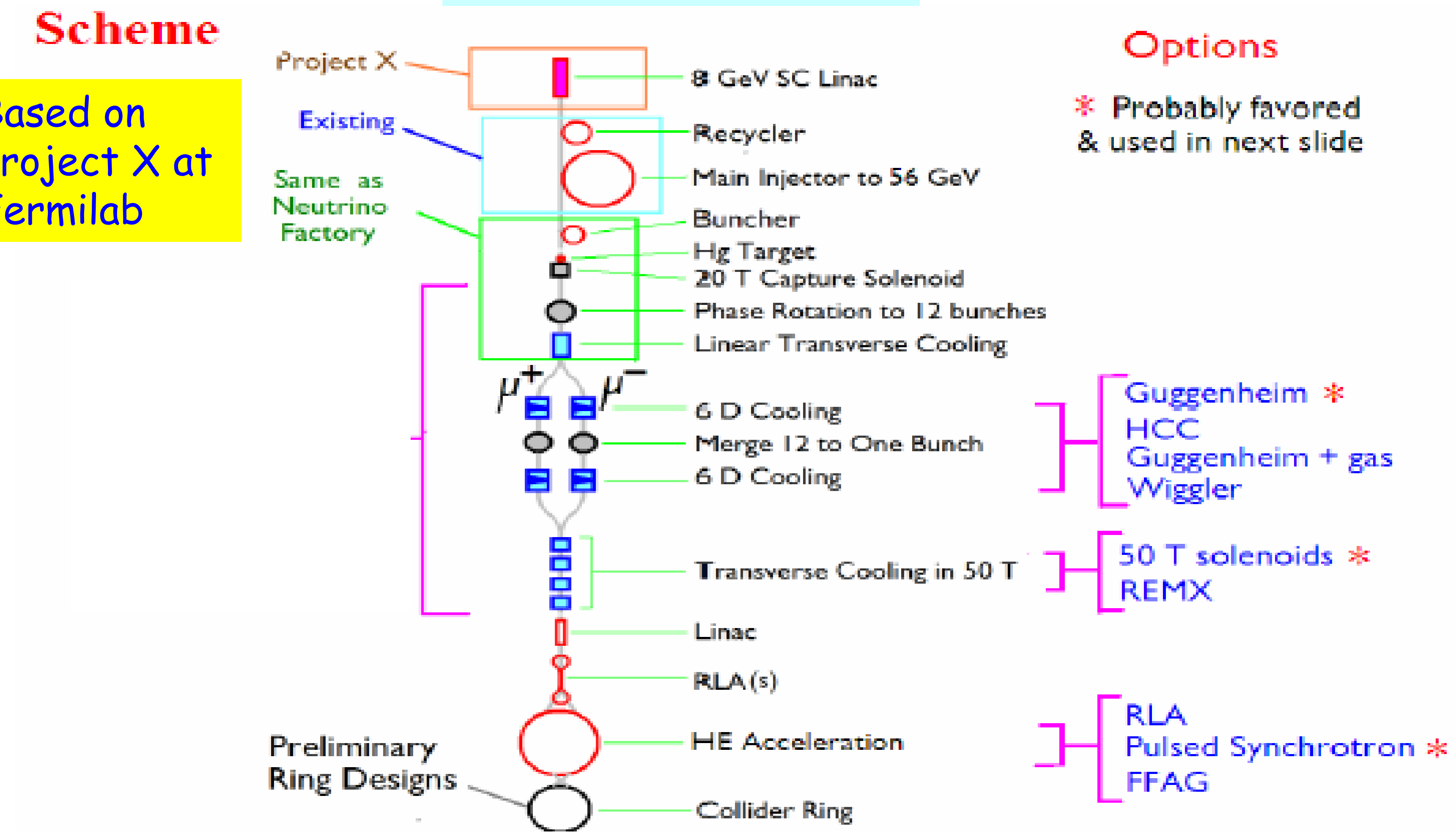
Drive beam - 95 A, 240 ns
from 2.4 GeV to 240 MeV

*True for ILC also if tunnel exists

Muon Collider Scheme

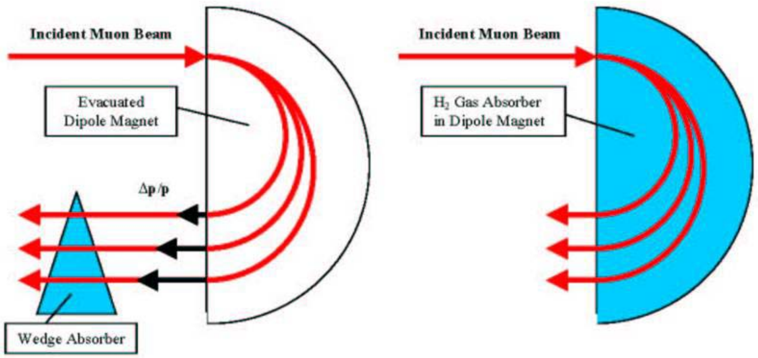
Fits on Fermilab site

Based on Project X at Fermilab



6D Cooling

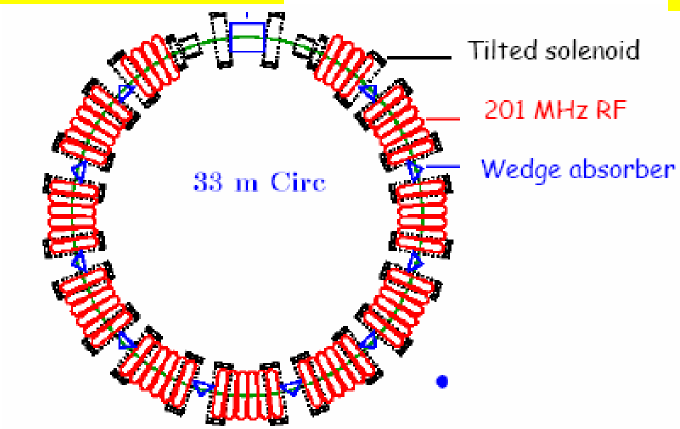
- For 6D cooling, add emittance exchange to the mix
  - increase energy loss for high-energy compared with low-energy muons
    - put wedge-shaped absorber in dispersive region
    - use extra path length in continuous absorber



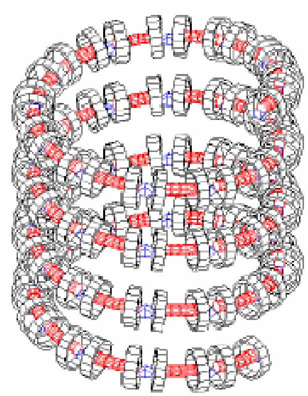
Gas-filled helical channel

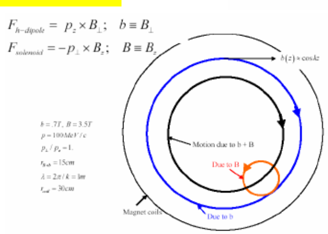
Issue: how to realistically incorporate RF into design

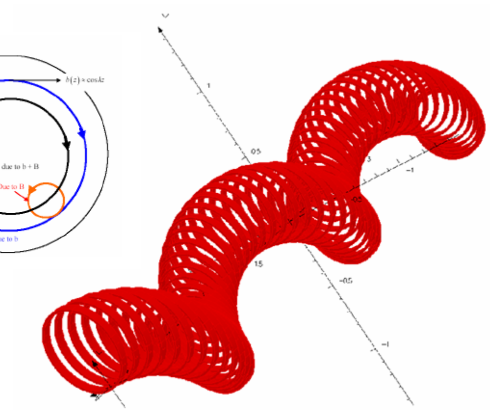
Cooling ring



"Guggenheim" channel





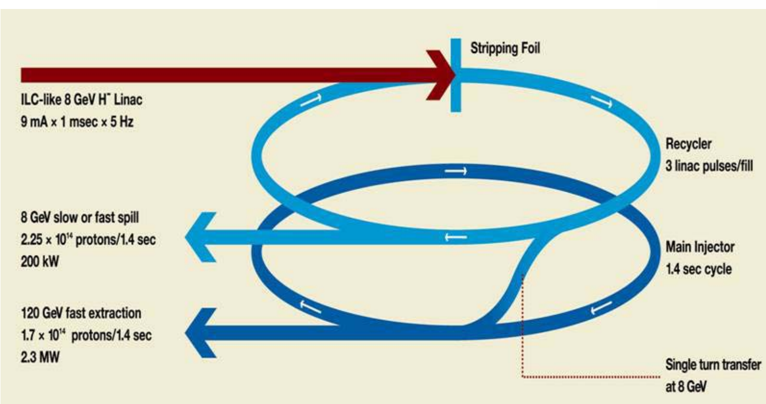


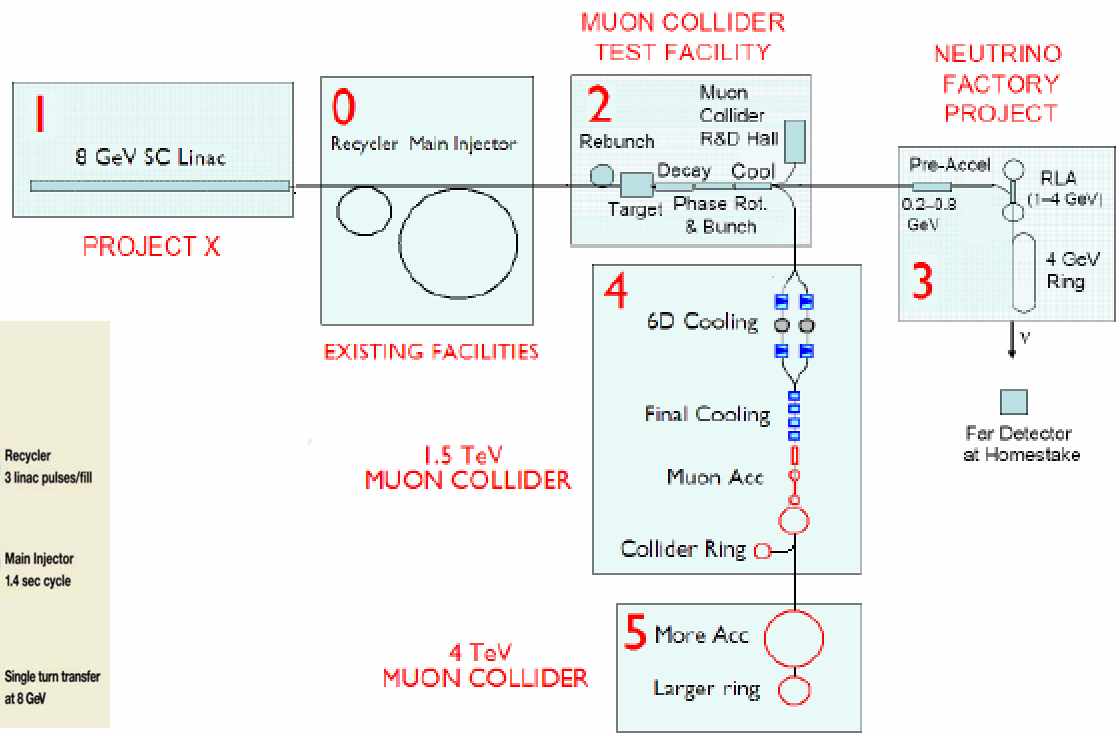
Phased Approach to Muon Facility

- Fermilab exploring path toward future muon beam facility
  - "imperative" is to keep Fermilab (the only active U.S. HEP lab) scientifically productive in the era when Tevatron has been shut down
    - expected in approx. 2010

Project X is the key!

It also develops U.S. capabilities toward ILC





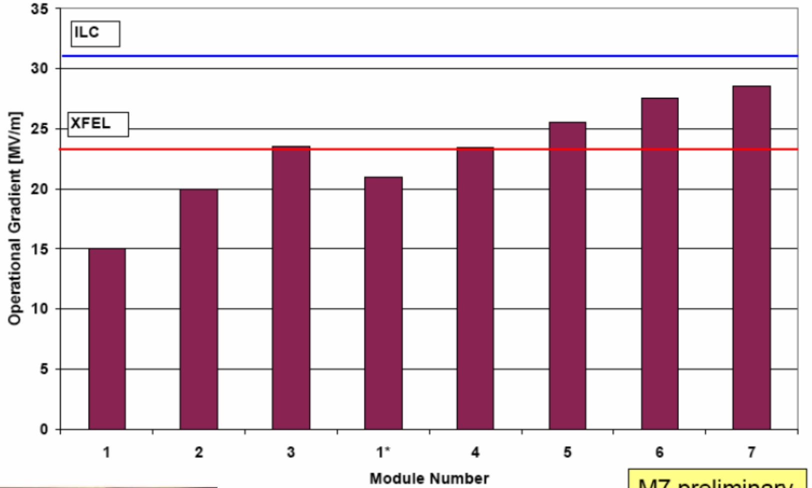
R&D Activities

- Putative projects covered here are embarked on R&D to:
  - prove physics concepts
  - validate technology choices
  - develop realistic, defensible cost estimates
- There are several "audiences" for the R&D results
  - the project advocates
  - the scientific community
  - ≥1 Laboratory directors
  - ≥1 funding agencies/governments
- While I cannot do justice to the complete R&D programs, I will attempt to give a flavor of what is under way

ILC R&D Program (1)

- **Primary effort for ILC is reaching design gradient with production cryomodules**

Producing Cavities



M7 preliminary

Making progress; not there yet

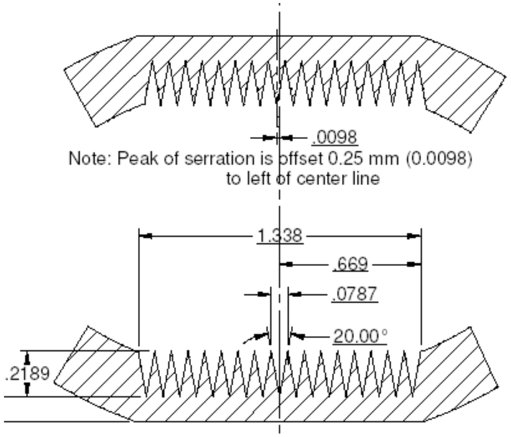
Cryomodule tests at DESY

ILC R&D Program (2)

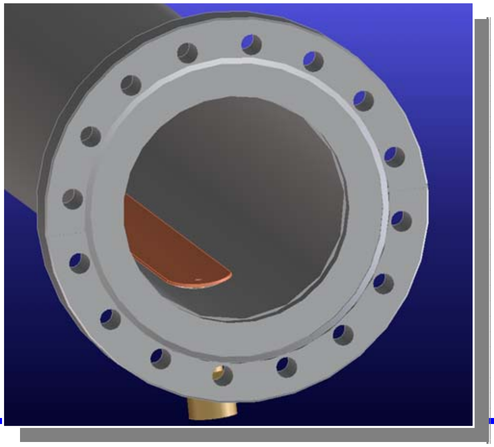
- **Another big technical concern is e-cloud effect in PDR**
  - issue is degradation of vertical emittance due to interaction with e-cloud

- **Initially addressed by simulations and tests of modified vacuum chamber designs at PEP-II**
  - testing "grooved" chambers and clearing electrodes
    - simulations indicate beneficial effects will keep DR parameters below instability threshold

Grooved chamber for PEP-II test

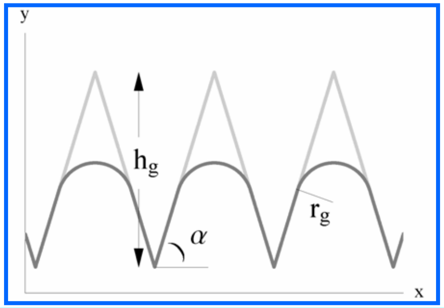


Clearing electrode chamber for PEP-II test



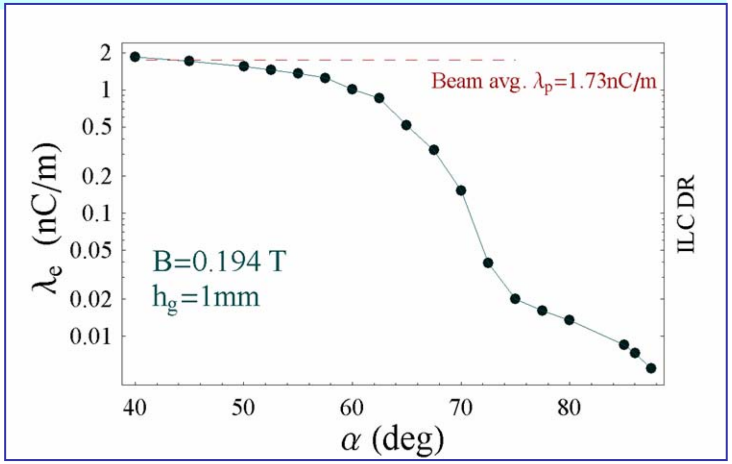
ILC R&D Program (3)

- **Simulations show that triangular groove geometry with a sufficiently steep angle can suppress e-cloud effectively**
  - *impedance considerations favor rounded grooves*

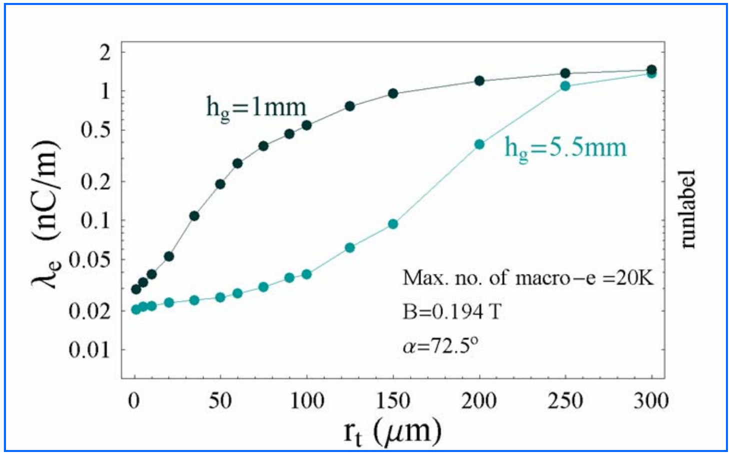


Proposed CESR-TA tests will measure these effects on beam under nearly DR conditions

Cloud density decreases 100-fold for sufficiently steep angle



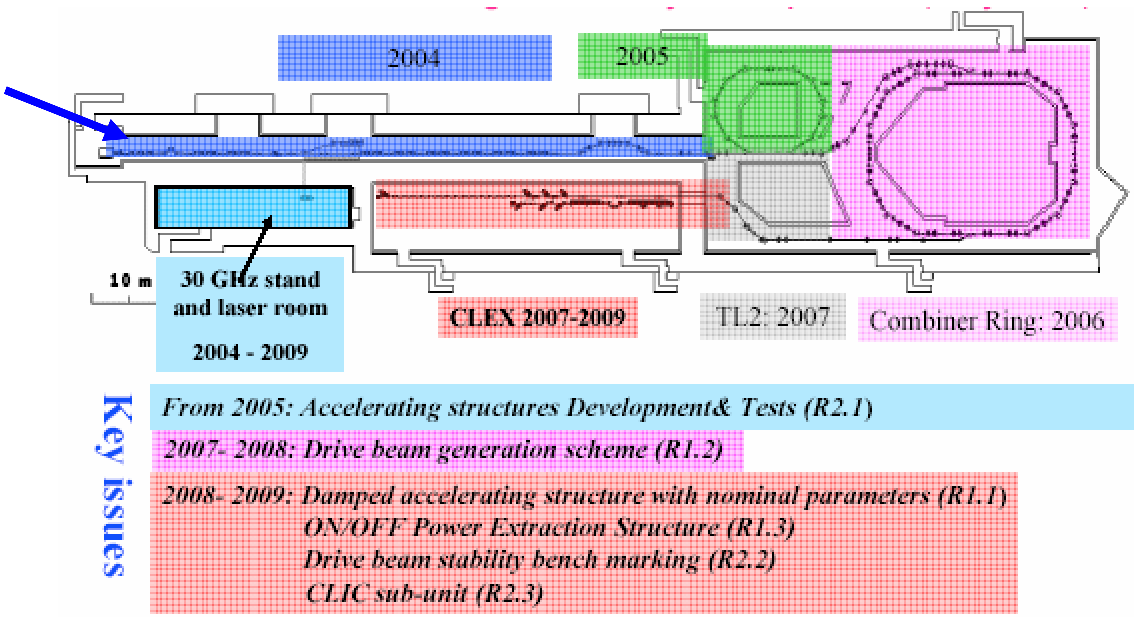
Adding tip radius helps impedance but spoils suppression effect



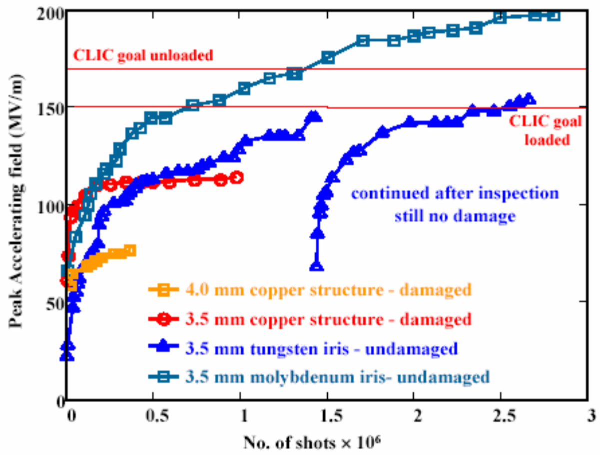
CLIC R&D Program (1)

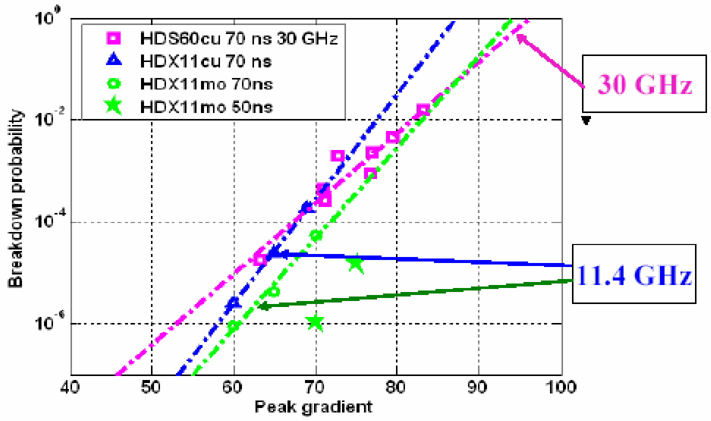
- Primary effort for CLIC is to demonstrate feasibility of CLIC technology (CTF3)
  - and estimate its cost
  - 19 countries currently involved in CLIC effort (centered at CERN)
    - coordination with ILC on issues of common interest, e.g., DRs

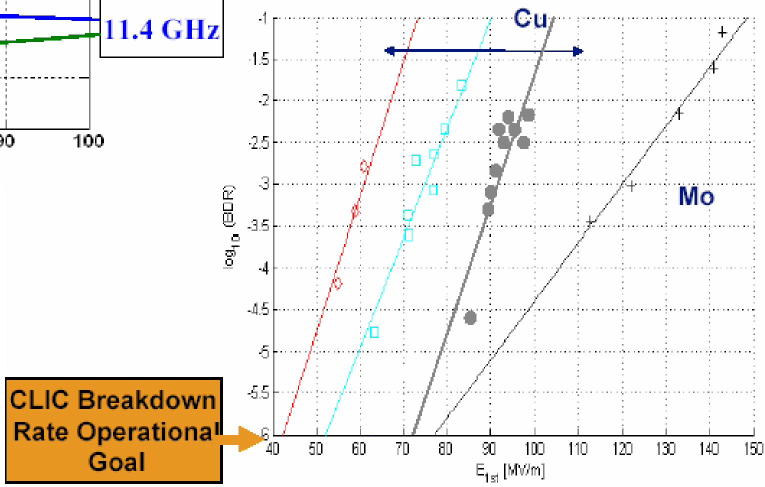
INJECTOR



- High gradients with “hard” materials demonstrated in CTF2
  - both Mo and W irises look workable (up to 190 MV/m!)
    - issue is breakdown rate, which is not yet acceptable for operation
      - breakdown criterion shows little frequency dependence



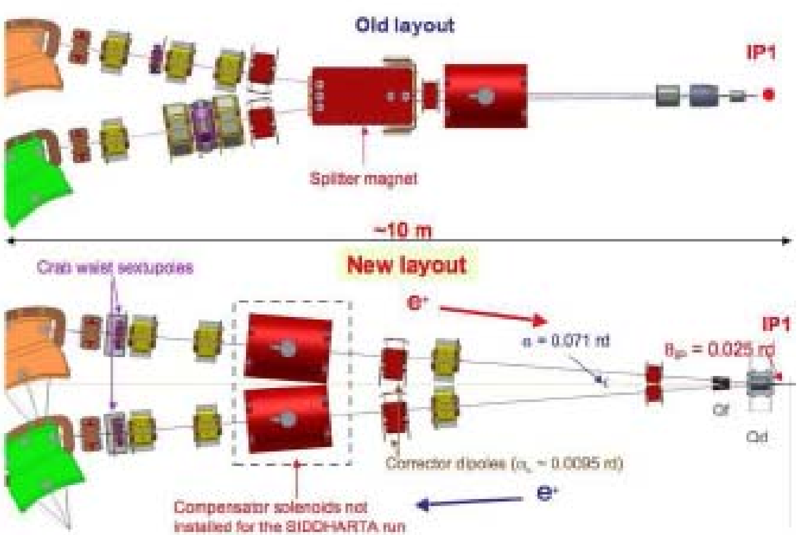




Super B Factory R&D (1)

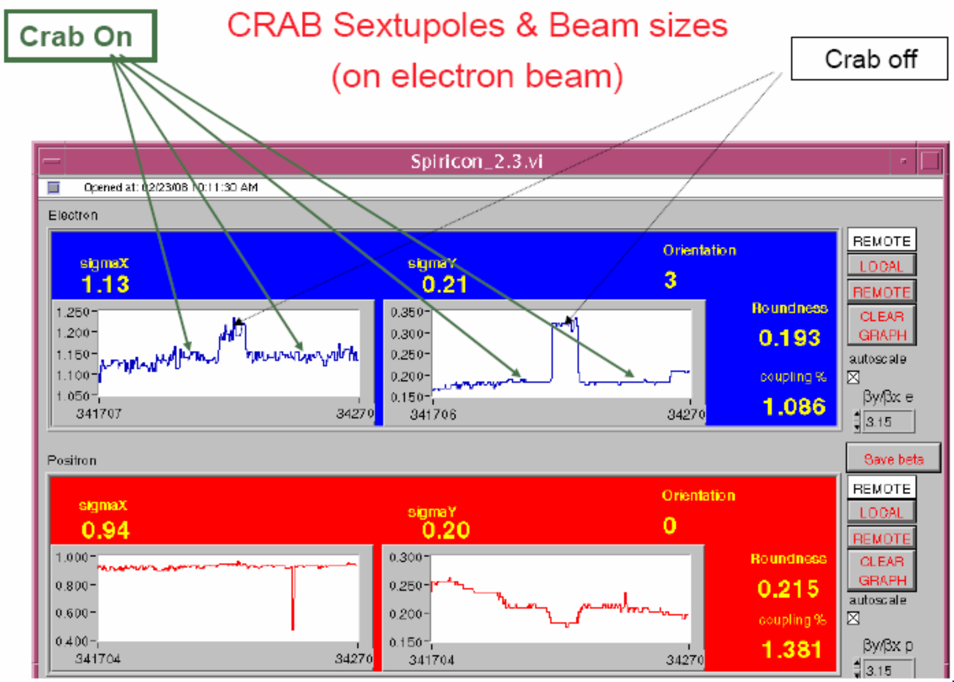
- Primary issues
  - does crab waist scheme work as expected?
  - can the IP beta value be low enough to get a x100 luminosity increase?

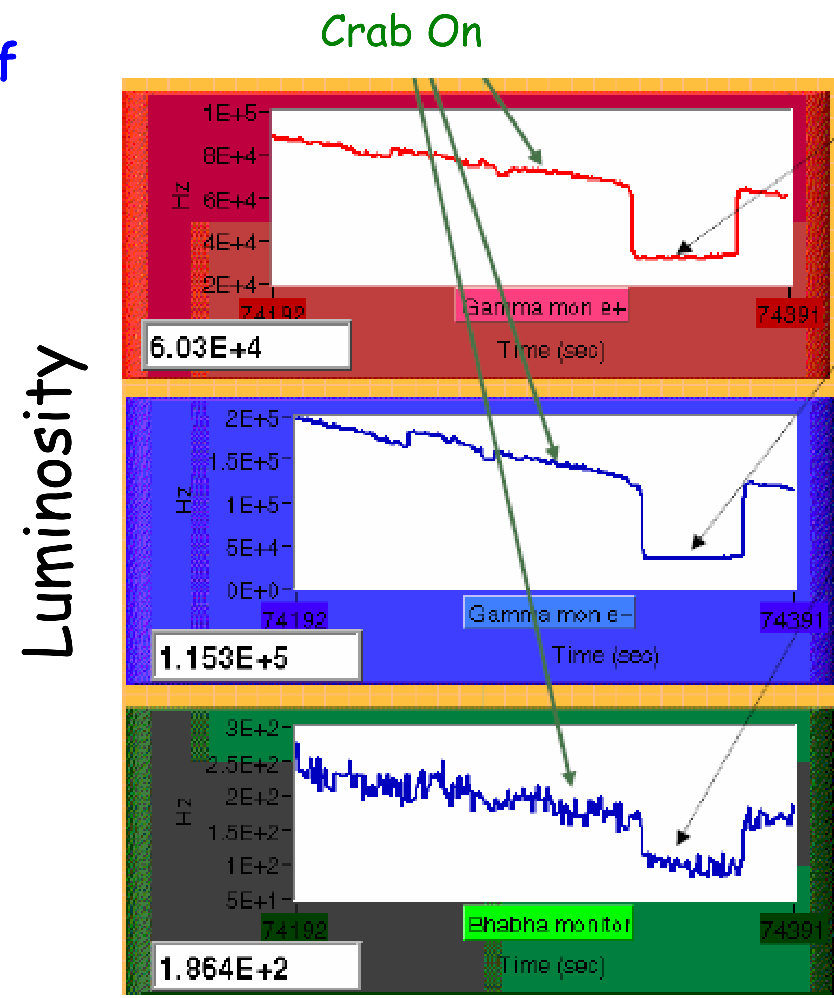
- Test of crab waist scheme at DAΦNE getting under way
  - modified IR to give crossing angle
    - sextupoles added to IR



Super B Factory R&D (2)

- Preliminary results show that crab sextupoles help
  - beam size increases when sextupoles off
  - luminosity decreases when sextupoles off





Muon Beam R&D Program

- Broad R&D program under way in all regions
  - Europe: various institutions sponsored by BENE and UKNF
  - Japan: NuFact-J group supported by university and some US-Japan funds
  - US: NFMCC program sponsored primarily by DOE with help from NSF
- Includes several international efforts already
  - MERIT (target test)
  - MICE (ionization cooling test)
  - EMMA (electron model of non-scaling FFAG)
  - IDS-NF (Neutrino Factory design study)
- Other experiments in planning stage
  - MANX (6D cooling)
  - Target test facility at CERN

Note: R&D effort relevant both to NF and MC

MuCool R&D (1)

- **MuCool program at Fermilab tests cooling components**
  - **RF cavities, absorbers**

Bross, Cummings, Ishimoto, Li, Moretti, Norem, Rimmer, Torun

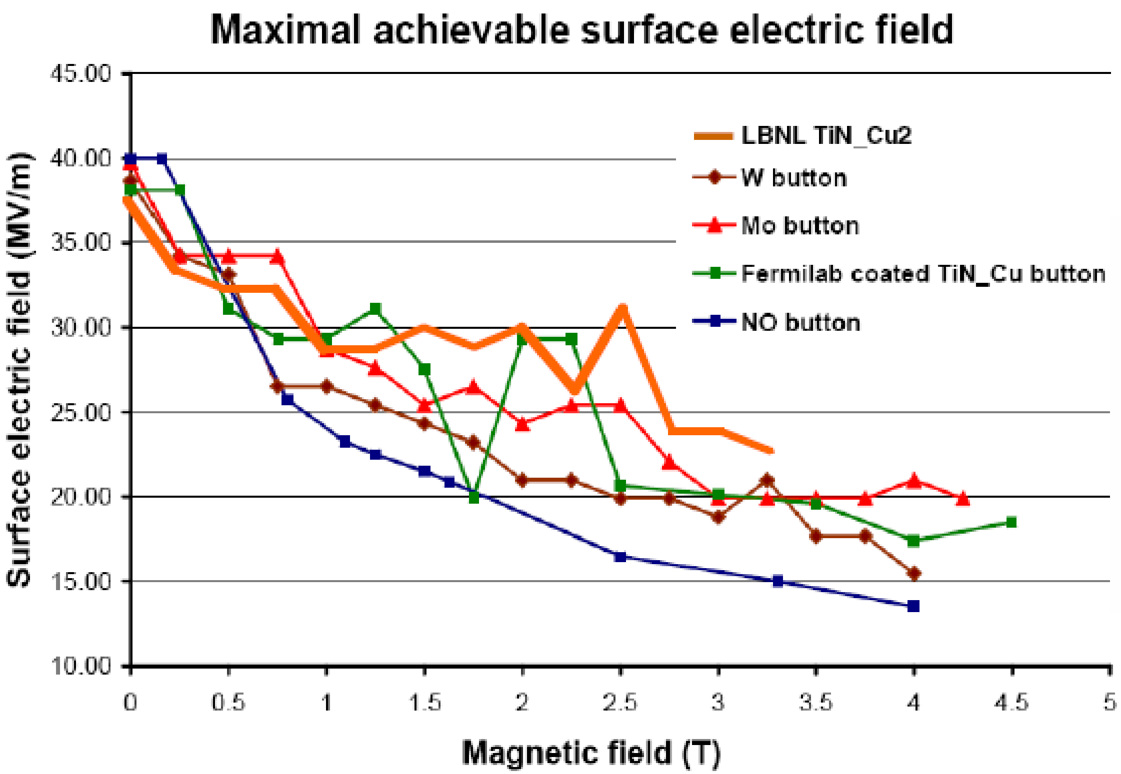
201 MHz cavity in MTA

805 MHz cavity

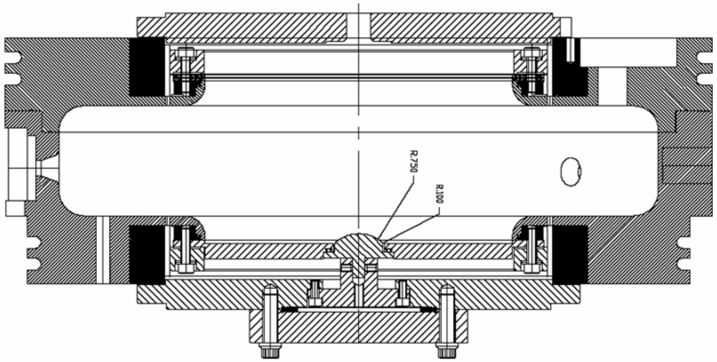
Convection-cooled LH_2 absorber

MuCool R&D (2)

- 805 MHz cavity tests in axial magnetic field show degradation in achievable gradient
  - need to understand this better
  - need to remeasure for 201 MHz cavity



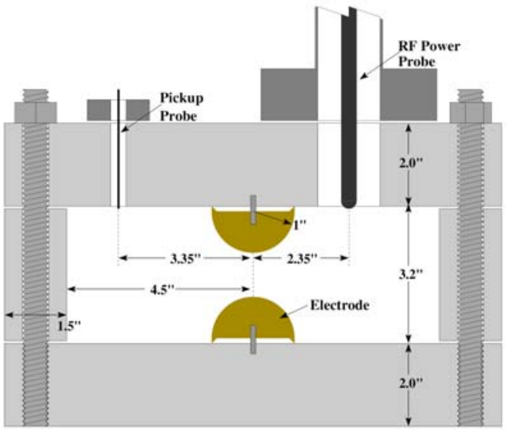
805 MHz "button" cavity



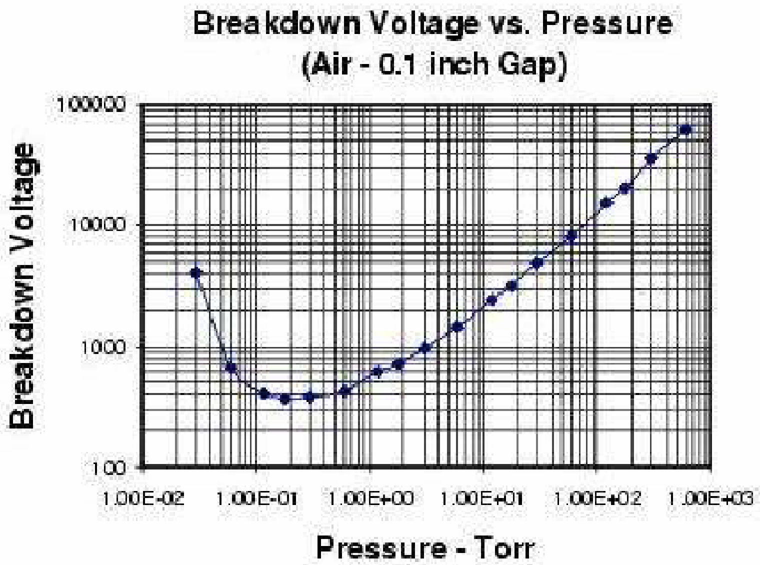
Pressurized Cavity R&D

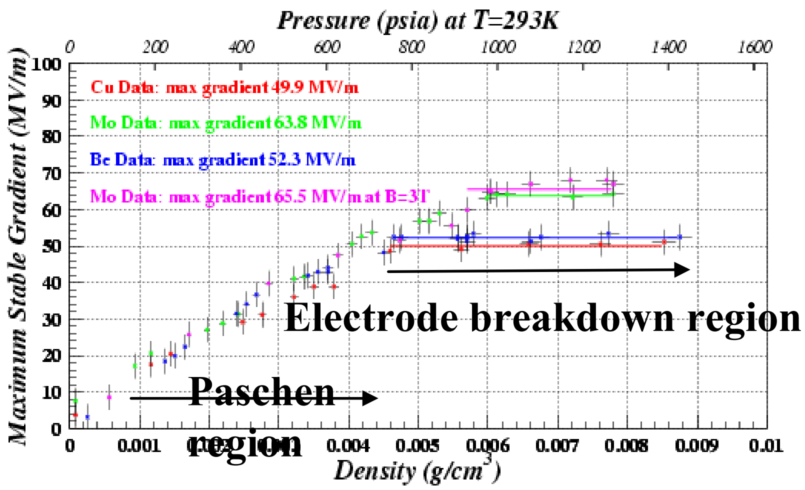
- Tested version of button cavity pressurized with H_2 gas
  - limit breakdown by Paschen effect

Remaining issue:
What happens when high intensity beam traverses gas?



Muons, Inc.

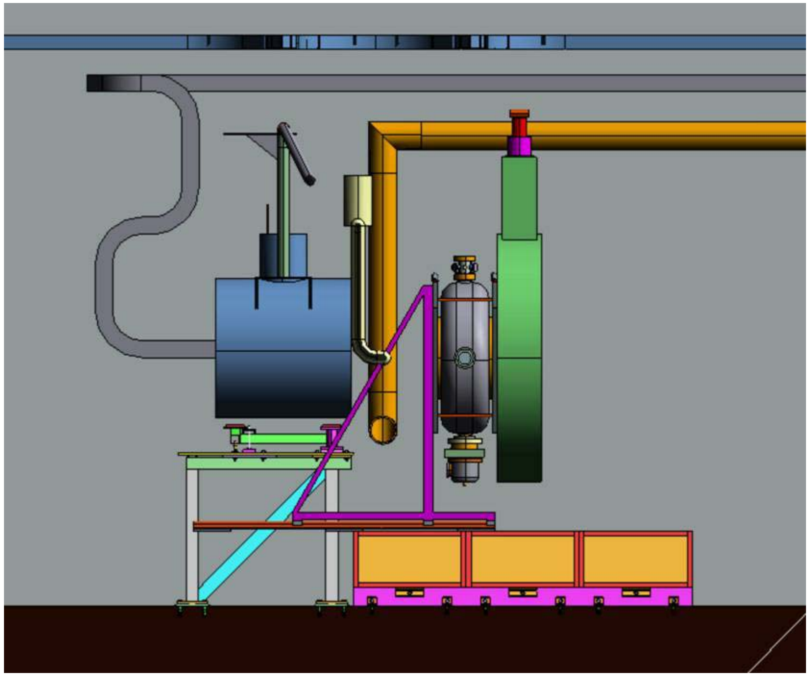




Cooling Channel RF

- Cooling channel requires high-gradient 201 MHz RF in a strong (solenoidal) magnetic field
  - prototype cavity built by LBNL-Jlab collaboration (Li, Rimmer, Virostek)
    - easily reached 19 MV/m design gradient without magnetic field at MTA
    - waiting for a Coupling Coil to test in high magnetic field

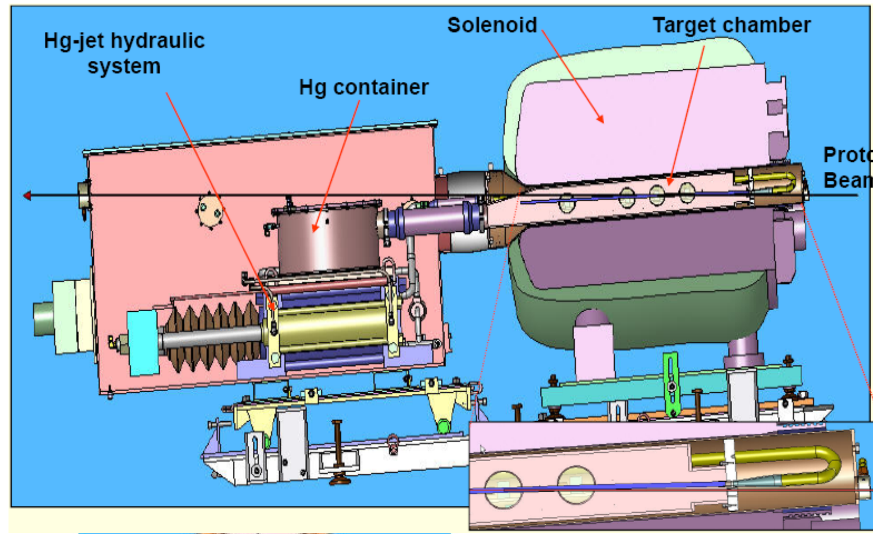
Setup for CC + cavity test

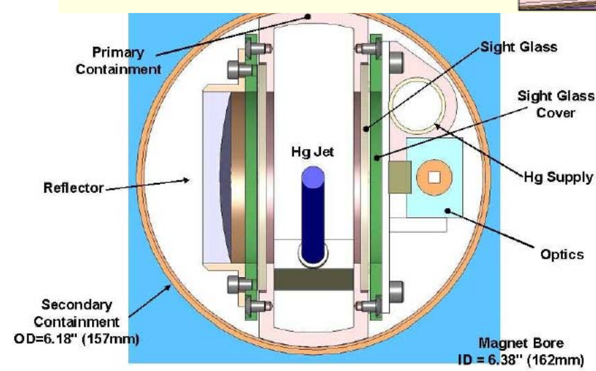


MERIT

- **MERIT experiment tested Hg jet in 15-T solenoid (Kirk, McDonald, Efthymiopoulos)**
  - 24 GeV proton beam from CERN PS
    - completed October 2007

15-T solenoid and Hg jet installed in TT2A tunnel at CERN



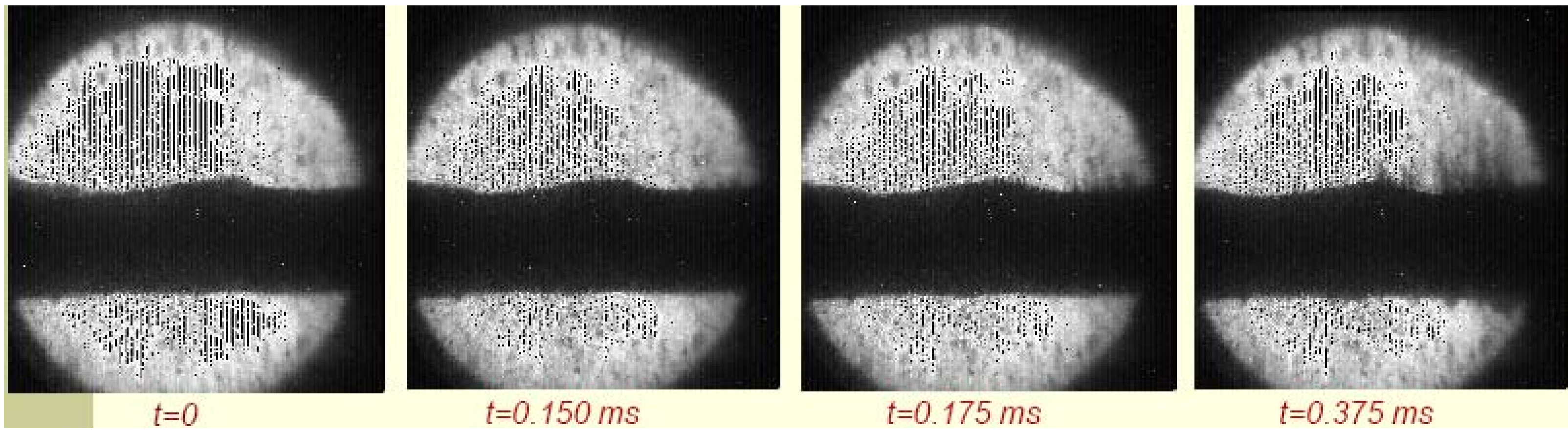


MERIT Results

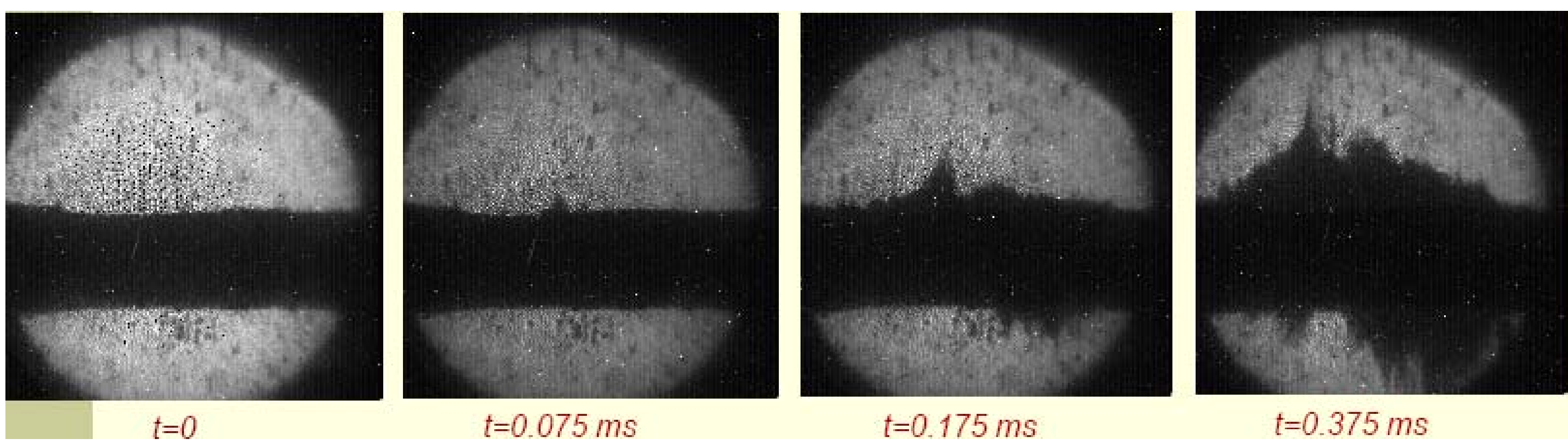
- **Analysis still under way ⇒ interpretation is preliminary**
  - **target reaction to beam comes well after the pulse**
    - **pictures with 10 T field**

P_{beam} beyond 4 MW is feasible

3.8 Tp



10 Tp



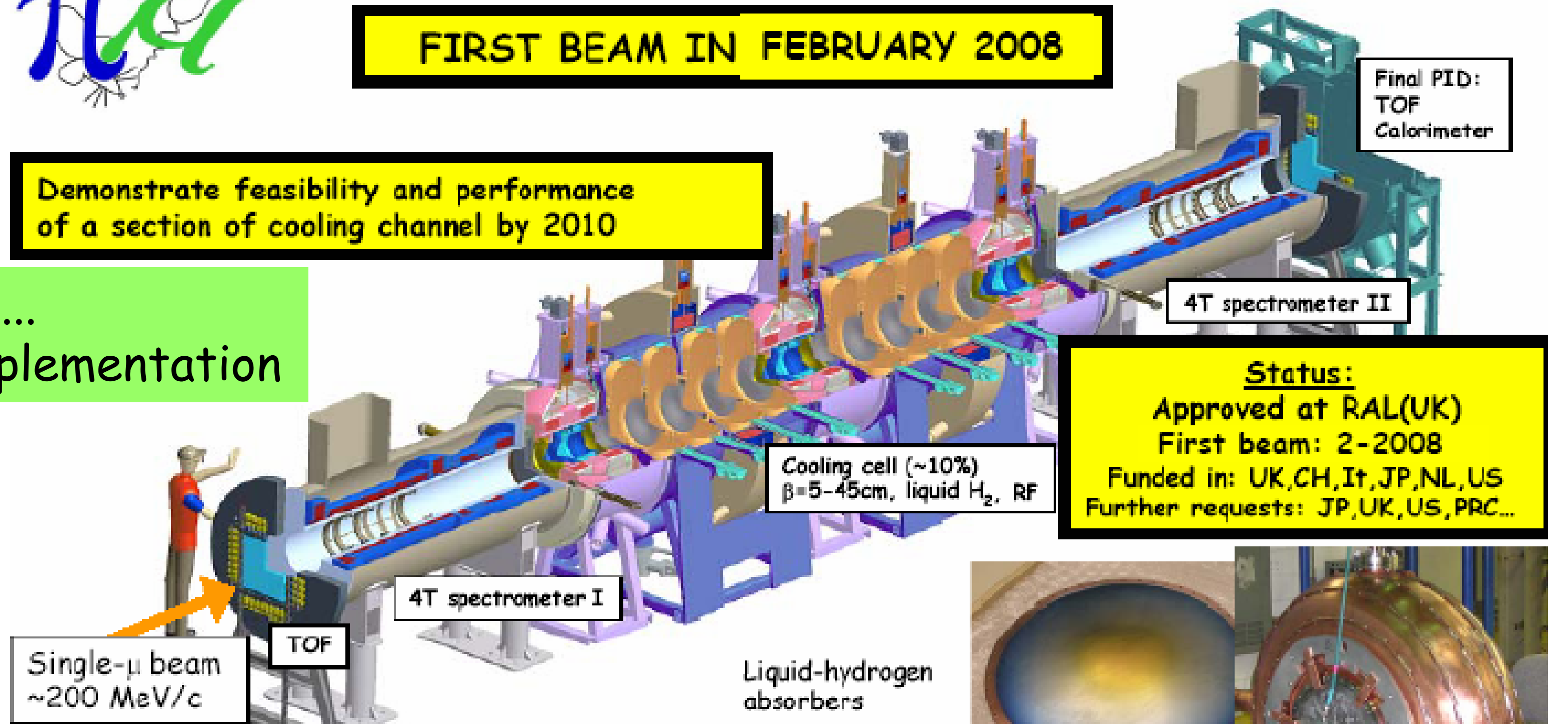
MICE

Muon Ionization Cooling Experiment

FIRST BEAM IN FEBRUARY 2008

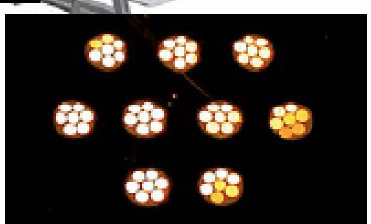
Demonstrate feasibility and performance of a section of cooling channel by 2010

Simple concept...
complicated implementation



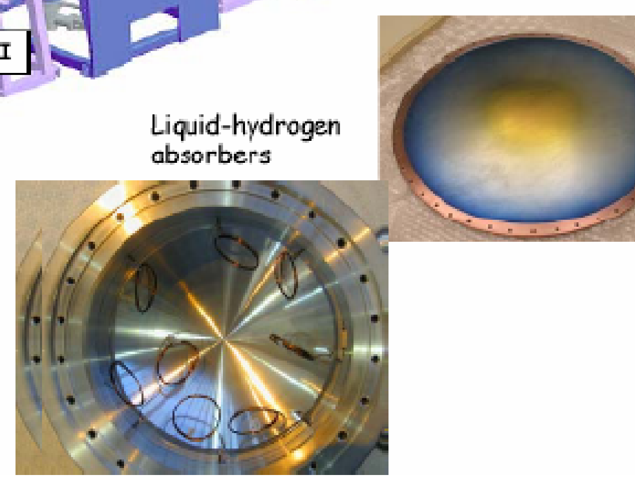
Status:
Approved at RAL(UK)
First beam: 2-2008
Funded in: UK,CH,It,JP,NL,US
Further requests: JP,UK,US,PRC...

Prototyping:



Scintillating-fiber tracker

Liquid-hydrogen absorbers

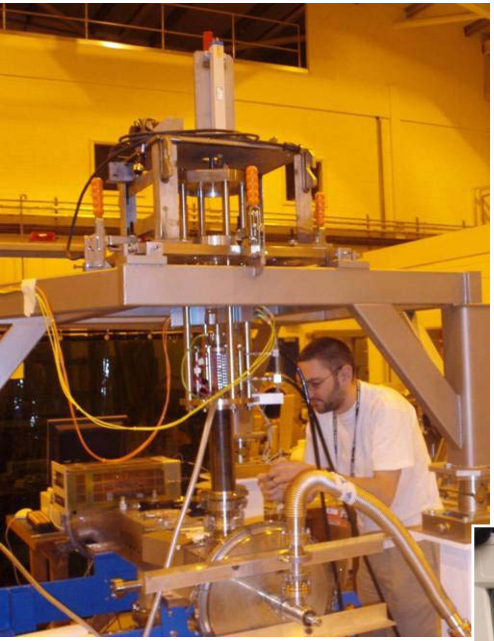


200MHz RF cavity with beryllium windows

Challenges:
RF in magnetic field
Proximity of RF and LH_2

MICE Beam Line

- Commissioning started at end of March 2008
  - decay solenoid not yet available, so commissioning with protons and pions

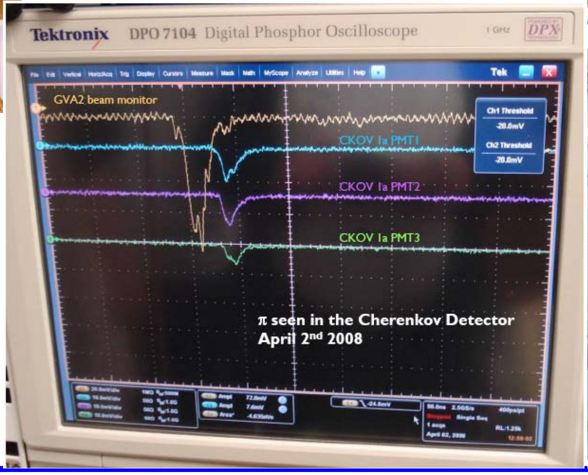


Target

Q1, Q2, Q3, D1

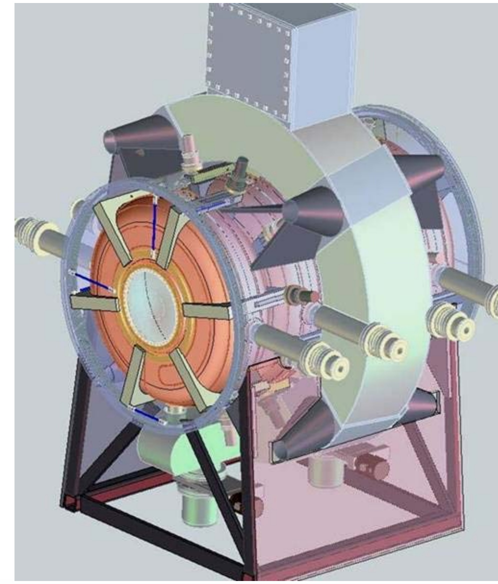
MICE Hall

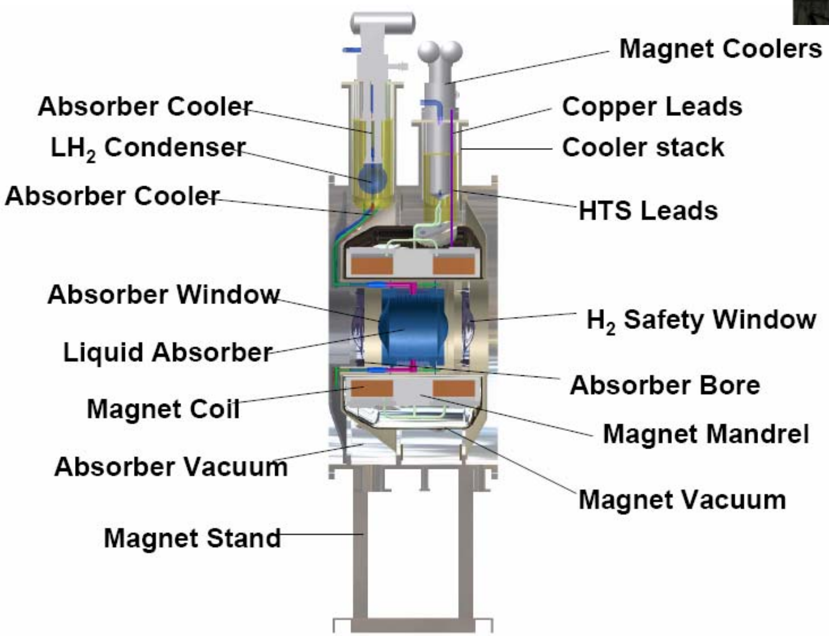
Pion in CKOV

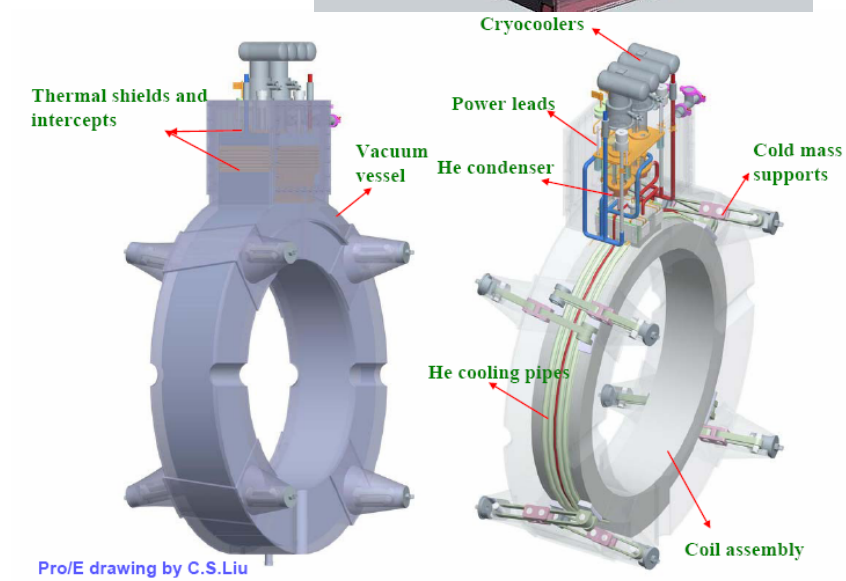


MICE Cooling Components

- Components being fabricated now
  - RFCC modules (US+China)
  - FC modules (UK)
  - absorbers (Japan+US+UK)

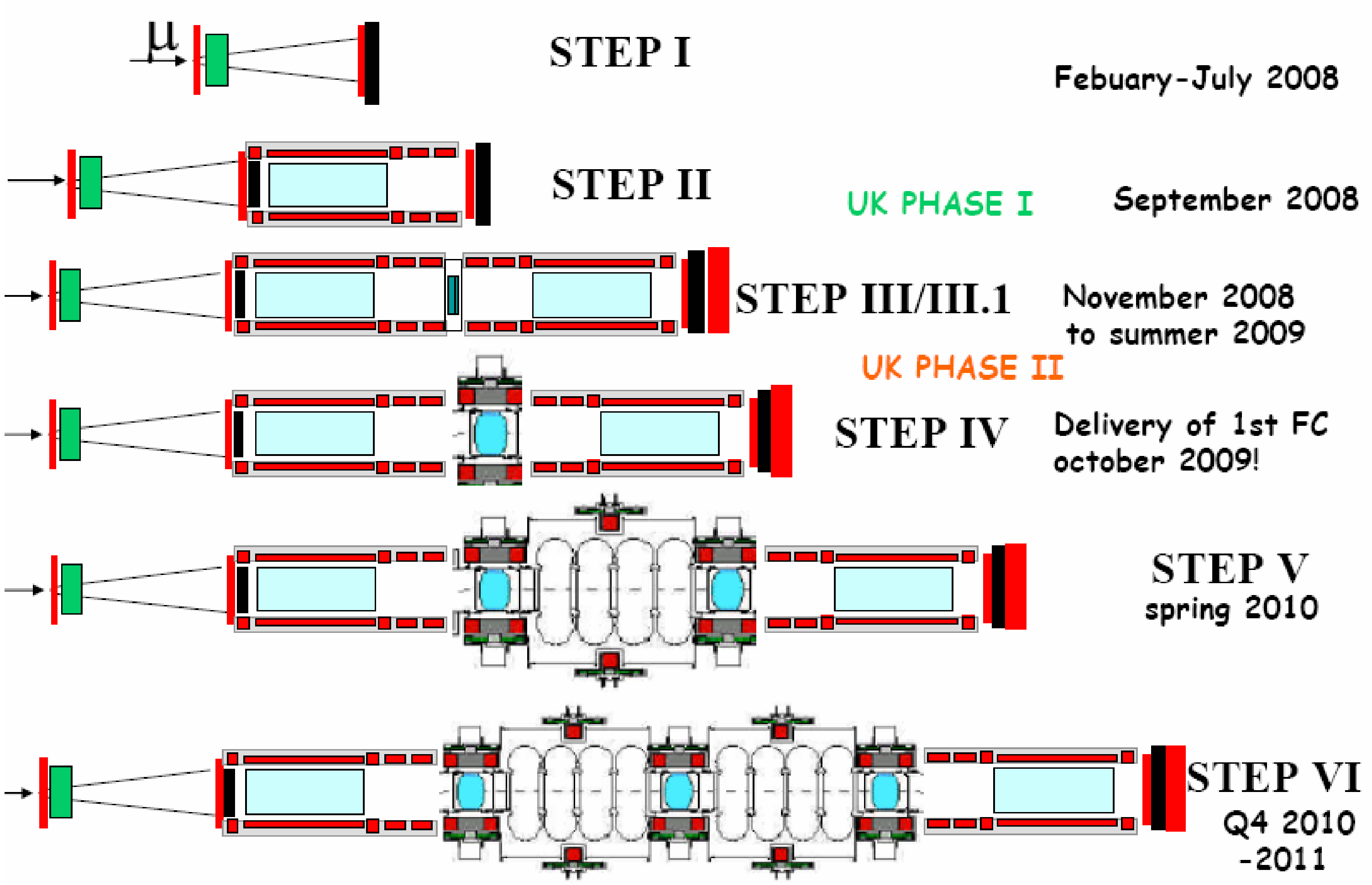






MICE Stages

- Present staging plan

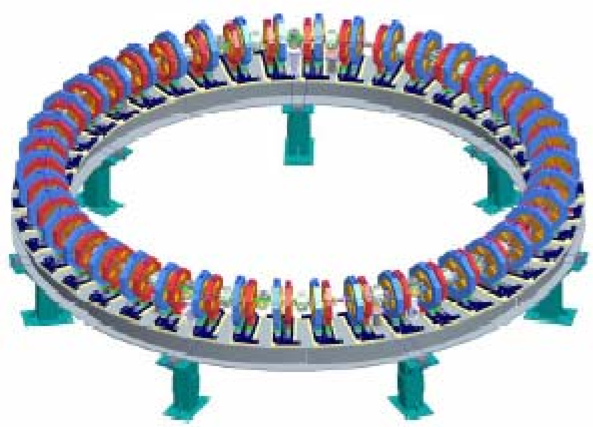


EMMA

- **EMMA will test an electron model of a non-scaling FFAG**
  - **uses Daresbury ERLP as injector**
  - **aim:**
    - **demonstrate feasibility of non-scaling FFAG concept**
      - **investigate longitudinal dynamics, transmission, emittance growth, influence of resonances**

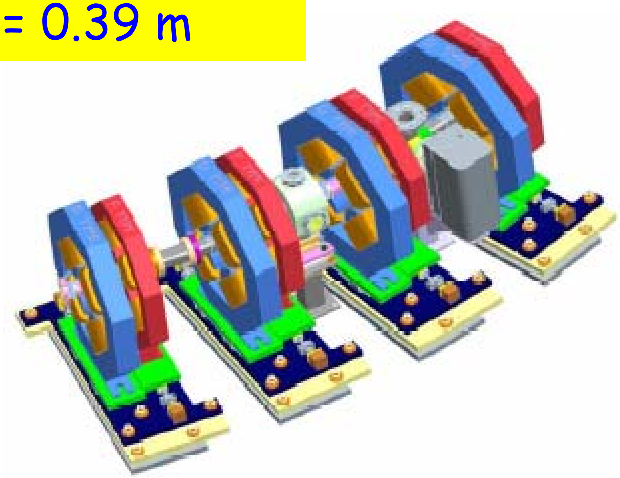
EMMA ring

C = 16.57 m



4 cells plus RF cavity

L_{cell} = 0.39 m



International Perspective

- International community holds annual "NuFact" workshops
  - provides opportunity for physics, detector, and accelerator groups to plan and coordinate R&D efforts at "grass roots" level
  - venue rotates among geographical regions (Europe, Japan, U.S.)

Year	Venue
1999	Lyon, France
2000	Monterey, CA
2001	Tsukuba, Japan
2002	London, England
2003	New York, NY
2004	Osaka, Japan
2005	Frascati, Italy
2006	Irvine, CA
2007	Okayama, Japan
2008	Valencia, Spain

Note: Muon Collider R&D presently a solely US activity; must change if there is to be a viable project

Points to Ponder

- What are the right tools from US perspective?
  - how critical is it to have one of these on US soil?
    - in particular, can Fermilab remain viable without having a major accelerator facility on-site?

- How should US accelerator R&D be prioritized?
  - ILC?* (Is *E* enough?)
  - CLIC? (Can US have substantial role?)
  - Super B? (Is it a big enough step scientifically?)
  - LHC? (Must participate, but is it sufficient to carry US program?)
  - Project X?* ← critical for future of Fermilab, especially if no ILC
  - Muon facilities (Neutrino Factory, Muon Collider)?* (Excellent scientific potential; are cost and technical risk acceptable?)

*possible US facility

- Should PD and AFRD priorities be coordinated toward one or a few options?

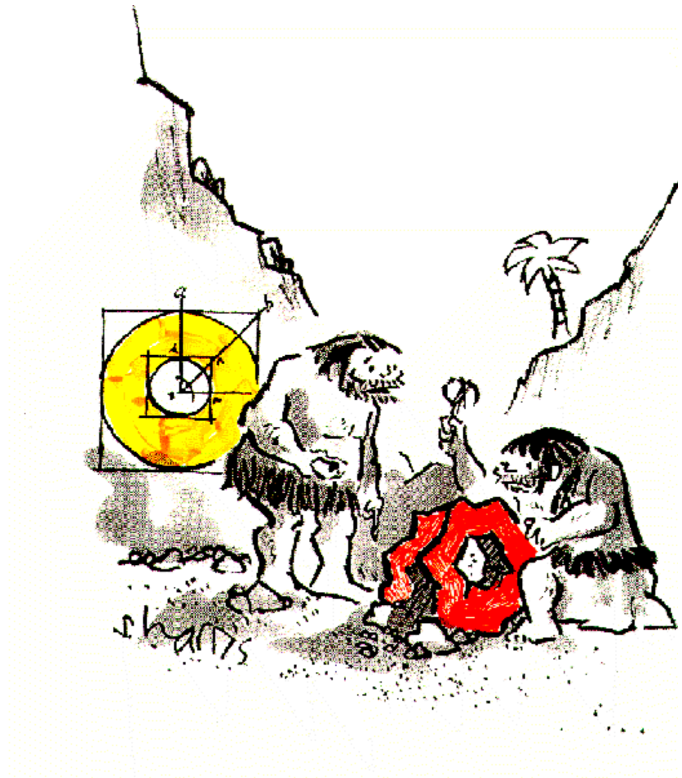
Summary

- Facilities now in the planning stage offer great potential to address the key outstanding questions in HEP
  - origins of mass
  - origin of matter-dominated universe
- R&D toward design of these new HEP facilities progressing on many fronts
  - from U.S. perspective, Project X is key to maintaining future options
- As with all accelerator R&D, success depends on synergy between accelerator physics and accelerator technology
  - in particular, control of instabilities and emittance will require state-of the-art diagnostics, feedback, RF, vacuum systems
- It would be beneficial to have coordinated priorities for LBNL's AFRD and PD
  - not necessarily identical, but at least mutually understood and supported

Final Thought

- Challenges of a future accelerator complex go well beyond those of today's beams
  - developing solutions requires substantial R&D effort to specify
    - expected performance, technical feasibility/risk, cost (matters!)

Critical to do experiments and build components.
Paper studies are not enough!



"I guess there'll always be a gap between science and technology."